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Geochemistry and mineralogy of late Quaternary loess in the upper Mississippi River valley, USA: Provenance and correlation with Laurentide Ice Sheet history

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A B S T R A C T

The midcontinent of North America contains some of the thickest and most extensive last-glacial loess deposits in the world, known as Peoria Loess. Peoria Loess of the upper Mississippi River valley region is thought to have had temporally varying glaciogenic sources resulting from inputs of sediment to the Mississippi River from different lobes of the Laurentide Ice Sheet. Here, we explore a new method of determining loess provenance using K/Rb and K/Ba values (in K-feldspars and micas) in loess from a number of different regions in North America. Results indicate that K/Rb and K/Ba values can distinguish loess originating from diverse geologic terrains in North America. Further, different loess bodies that are known to have had the same source sediments (using other criteria) have similar K/Rb and K/Ba values. We also studied three thick loess sections in the upper Mississippi River valley region. At each site, the primary composition of the loess changed over the course of the last glacial period, and K/Rb and K/Ba values parallel changes in carbonate mineral content and clay mineralogy. We thus confirm conclusions of earlier investigators that loess composition changed as a result of the shifting dominance of different lobes of the Laurentide Ice Sheet and the changing course of the Mississippi River. We conclude that K/Rb and K/Ba values are effective, robust, and rapid indicators of loess provenance that can be applied to many regions of the world.

1. Introduction

Similar to the famous loess deposits of China (Liu, 1988; Liu and Ding, 1998; Sun, 2002), some of the most extensive deposits of last-glacial-age loess on the planet are found in the mid-continental region of North America (Fig. 1). This loess is typically referred to as “Peoria Loess” or “Peoria Silt,” based on the thick deposits found near Peoria, Illinois (Smith, 1942; Willman and Frye, 1970; Hansel and Johnson, 1996). Peoria Loess deposits in mid-continental North America are derived from a wide variety of sources. In the Great Plains region west of the Missouri River (Fig. 2), loess is derived from both glacial and non-glacial sources (Aleinikoff et al., 1999, 2008; Muhs et al., 1999, 2008a; Yang et al., 2017). Farther east, however, near the southern terminus of the Laurentide Ice Sheet in the greater Mississippi River drainage basin (Fig. 2), a classical glacial model for the origin of loess has been established for more than a century (Chamberlin, 1897). This model proposes that loess accumulated as a result of the eolian transport of silt from valley-train outwash that, in turn, was derived from the till of the Laurentide Ice Sheet. Outwash from this ice sheet filled the valleys of the Mississippi River and its tributaries, the Missouri River, Illinois River, Wabash River, and Ohio River, during the most recent glacial periods. The model of glacial outwash as the major supplier of loess in the greater Mississippi River drainage basin withstood the test of time for many decades (see reviews in Ruhe [1983]; Bettis et al., [2003]; and Muhs [2013]), although non-glacial sources may have been a secondary sediment contributor (Frye et al., 1962; Ruhe and Olson, 1980; Grimley, 2000).

Since Chamberlin's time, however, a number of studies have demonstrated that Peoria Loess has a compositional variability in sections thick enough to record the entire last glacial period in detail. Thick Peoria Loess in Illinois (Figs. 2 and 3) has a number of compositional zones that can be differentiated on the basis of clay mineralogy (Frye et al., 1968), carbonate mineral content (McKay,

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Fig. 1. Map of North America and adjacent islands showing the distribution of loess and the extent of ice sheets during the last glacial period. Loess distribution in Alaska is from Péwé (1975); loess adjacent to the Snake River Plain is from Lewis and Fosberg (1982); Palouse loess distribution is from Busacca and McDonald (1994). Loess in other regions is from sources given in Fig. 2; ice sheet extent is from Dyke et al. (2002). Note also that loess is found in some areas northward of the maximum southern extent of the Laurentide Ice Sheet and appear as dark brown delineations. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

1977, 1979a; 1979b), magnetic mineral content (Grimley et al., 1998), and silicate mineral content (Grimley, 2000). These differing compositions have been interpreted as the result of delivery of temporally varying proportions of glaciogenic silt ultimately derived from different lobes of the Laurentide Ice Sheet. Different ice lobes traversed terrains with distinct bedrock compositions. Adding to this complex picture, it is necessary to consider the changes in the drainage systems that were affected by movements of the Laurentide Ice Sheet. Perhaps the most dramatic example of this was the diversion of the Mississippi River at ~24.4 ka (in calibrated years; note that all radiocarbon ages throughout the text are in calibrated years unless otherwise noted) that resulted from the advance of the Lake Michigan Lobe (Figs. 2 and 3) of this ice sheet (Shaffer, 1954; Frye et al., 1962, 1968; Glass et al.,

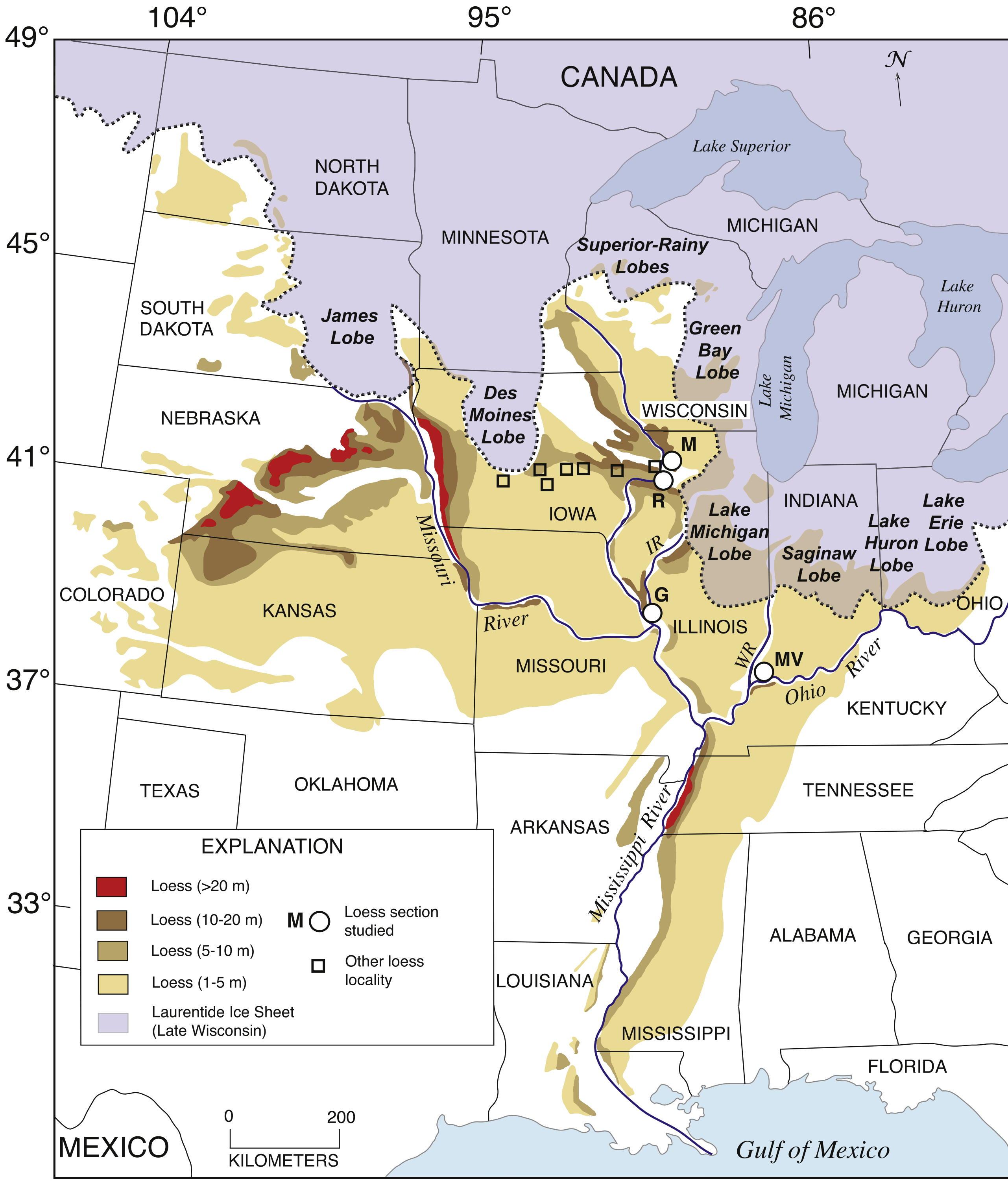

Fig. 2. Loess distribution and thickness in the central United States based on the following sources: Clayton et al. (1976) for North Dakota; Fullerton et al. (1995) for North Dakota and South Dakota; Welch and Hale (1987) and Denne et al. (1993) for Kansas; Muhs et al. (1999) for Colorado; Swinehart et al. (1994) for Nebraska and South Dakota; Mason (2001) for Nebraska; Whitfield et al. (1993) for Missouri; Hallberg et al. (1991) for Iowa; Hole (1976) for Wisconsin; Smith (1942) and Fehrenbacher et al. (1965a, 1986) for Illinois and Indiana; Wascher et al. (1948) and Miller et al. (1988) for Kentucky, Tennessee, and Mississippi; Heinrich (2008) for Louisiana; Moore et al. (2009) for parts of Indiana and Kentucky; and Thorp and Smith (1952) for other states. Note that thinner (<1 m) loess is found in some additional areas, not shown here (see, for example, Schaetzl and Attig [2013] and Schaetzl et al., [2014] for Wisconsin). Extent of ice sheet during the last glacial period (purple) is taken from Dyke et al. (2002); ice lobe names are from Mickelson and Colgan (2003). Note also that loess is found in some areas northward of the maximum southern extent of the ice sheet. M, Morrison; R, Rapids City; G, Greenbay Hollow; MV, Mount Vernon. IR, Illinois River; WR, Wabash River. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

1964; Curry, 1998; Grimley et al., 1998).

Using clay mineralogy, Frye et al. (1968) reported what they called Zones I, II and IV, from oldest to youngest, within Peoria Loess along the Mississippi River. Zone I is characterized by low

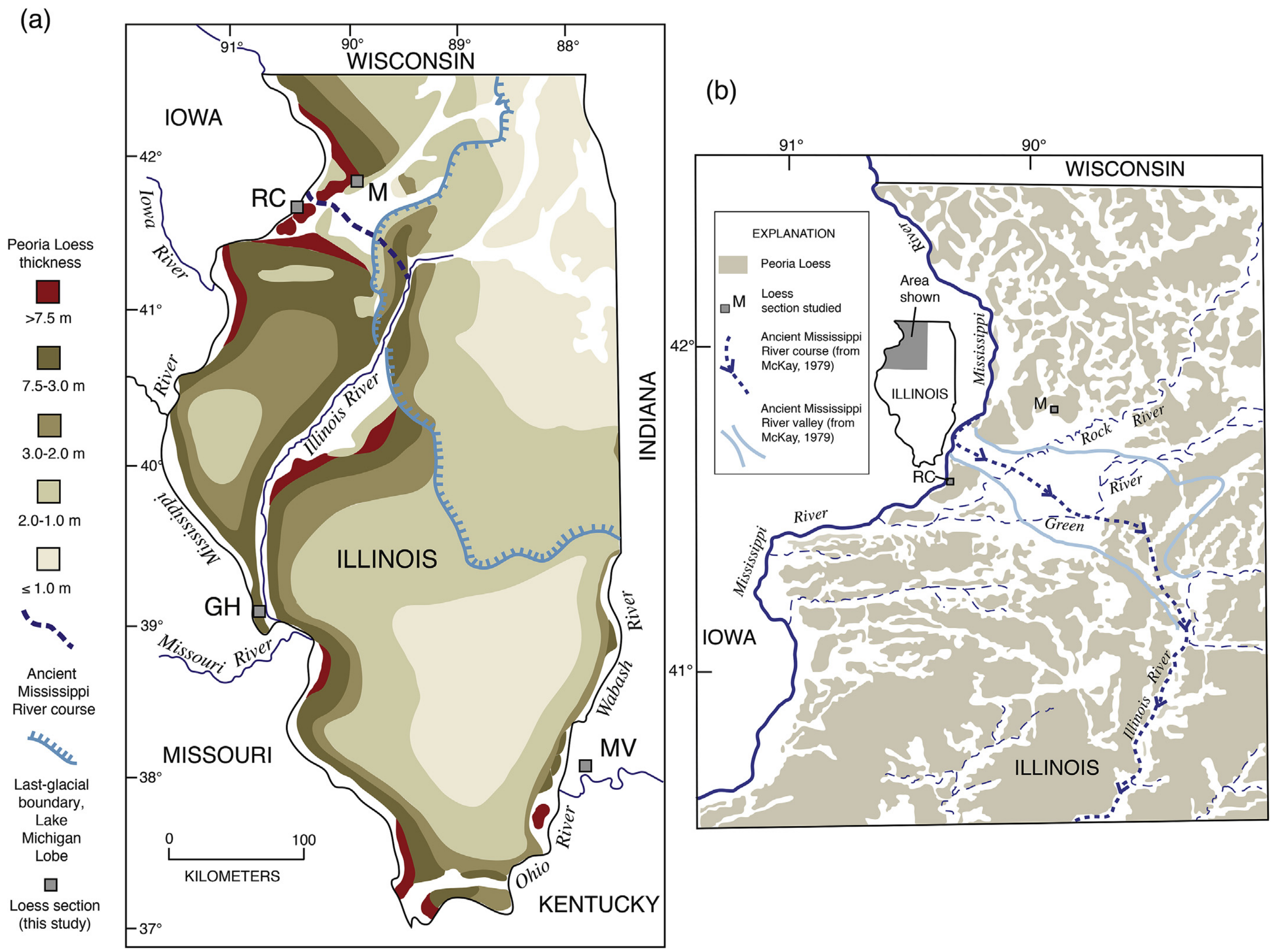

Fig. 3. (a) Distribution of Peoria Loess in Illinois, redrawn from Fehrenbacher et al. (1986). Also shown are the extent of the Lake Michigan Lobe of the Laurentide Ice Sheet (blue) at the last glacial maximum, the course of the Ancient Mississippi River (dashed line; terminology from Frye et al., [1968]), redrawn from McKay (1979a), and the location of loess sections studied (grey squares). M, Morrison; RC, Rapids City; GH, Greenbay Hollow; MV, Mount Vernon. (b) Detailed map of the distribution of Peoria Loess in the northwestern part of Illinois (redrawn from Illinois State Geological Survey loess thickness map; accessed November, 2010 [http://isgs.illinois.edu/content/loess-thickness-map]). Also shown are the course of the Ancient Mississippi River (dashed line) and its valley sides (light blue lines), redrawn from McKay (1979a; and written communication, 2010) and the location of loess sections studied (grey squares). M, Morrison; RC, Rapids City. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

illite, Zone II by intermediate illite, and Zone IV by low illite. Frye et al. (1968), working elsewhere in Illinois, also reported a Zone III, characterized by very high illite content. This zone, however, is found only in loess along the Illinois River valley (Fig. 3). Although the focus of the study by Frye et al. (1968) was on loess zonation using clay minerals, they also reported semiquantitative data on carbonate mineral (dolomite and calcite) abundances. Their data show that zones of high illite also have high amounts of dolomite. Following on this observation, McKay (1977, 1979a, 1979b) used quantitative carbonate mineral abundances, primarily dolomite, to identify distinct mineral zones (p-1, p-2, p-3, p-4, p-5, and p-6, from oldest to youngest) within Peoria Loess in southwestern Illinois. Zones p-1, p-4, and p-6 are zones of low dolomite, zones p-2 and p-5 are high dolomite, and zone p-3 has intermediate amounts of dolomite. McKay (1979a) correlated his dolomite zones with Frye et al.'s (1968) clay mineral zones and confirmed that zones of high illite are also zones of high dolomite. Frye et al. (1968) and McKay (1979a) interpret low-illite, low-dolomite loess, adjacent to the Mississippi River valley in Illinois, to reflect derivation primarily from glacial sources to the northwest, in Minnesota and Iowa (Fig. 2). In contrast, high-illite, high-dolomite loess is interpreted to reflect glacial sources to the northeast, in Wisconsin and Michigan. Grimley et al. (1998), working along the Illinois River, identified three distinctive zones within Peoria loess (lower, middle, upper) based on magnetite content, as expressed by low-field magnetic susceptibility. Grimley (2000) extended this work to quantify loess sources along the Illinois River valley in Illinois using a combination of magnetite, feldspar, dolomite, and illite contents.

To complement the methods described above, the provenance of loess can also be determined using geochemical methods. Muhs et al. (2008a, 2013) reported that K/Rb and Ba/Rb values, representing varying compositions of K-feldspars and micas, have the capability to distinguish loess of different provenance in Alaska, Nebraska and Iowa. To our knowledge, a geochemical approach to loess provenance has not yet been applied in the classical areas of study along the Mississippi River and Illinois River. Nevertheless, K-feldspar and mica are common minerals in the loess of this region (Frye et al., 1962, 1968; Grimley, 2000) and therefore an approach using K, Ba, and Rb could potentially be applied to these sediments. Given the diversity of the lithologies supplying silt- and clay-sized

Table 1
Radiocarbon ages of materials from loess sections (Indianaand Illinois) or till sections (Iowa).

Laboratory #	Field #	Depth in loess section (m) and/or stratigraphic context	Material dated	$\delta^{13}C$ (‰ vpdb)	^{14}C age	± (1σ)	Cal age*	± (2σ)	Reference
MOUNT VERNON, INDIANA, LOESS SECTION									
WW-7116	IN-180	3.3, Peoria Silt	Succineidae	-5.6	19800	100	23790	280	Pigati et al. (2015)
WW-7117	IN-185	5.8, Peoria Silt	Succineidae	-5	19340	90	23280	290	Pigati et al. (2015)
WW-8515	IN-1995b	12.8, Peoria Silt	*Hendersonia occulta*	-6.3	24460	110	28490	280	Pigati et al. (2015)
WW-8514	IN-1995a	12.8, Peoria Silt	*Inflectarius inflectus*	-8.8	24930	120	28990	330	Pigati et al. (2015)
WW-7318	IN-199S	12.8, Peoria Silt	Succineidae	-8	24920	200	29000	450	Pigati et al. (2015)
WW-7319	IN-201/202	13.5, Upper Farmdale Soil	Succineidae	-10.6	26480	210	30690	380	Pigati et al. (2015)
WW-7115	IN-207/208	15.0, “Lower” paleosol	charcoal	-24.19	37060	870	41300	1460	This study
RAPIDS CITY, ILLINOIS LOESS SECTION									
Aeon 2363	IL-311	5.0, Peoria Silt	Succineidae	-6.8	17540	100	21200	320	This study
Aeon 2364	IL-314	6.5, Peoria Silt	Succineidae	-7.9	19180	110	23130	340	This study
Aeon 2352	IL-321	8.6, Peoria Silt	wood	-31.1	20790	130	25010	430	This study
WW-2170	IL-321	8.6, Peoria Silt	spruce needles	-25	21110	70	25450	210	Muhs et al. (2001)
WW-2153	IL-324	9.4, Upper Farmdale Soil	humic acids	-25	23410	90	27600	180	Muhs et al. (2001)
Aeon 2354	IL-324	9.4, Upper Farmdale Soil	wood	-28.2	23840	170	27960	340	This study
WW-2154	IL-326	9.9, Lower Farmdale Soil	humic acids	-25	27210	160	31160	220	Muhs et al. (2001)
WW-2156	IL-326	9.9, Lower Farmdale Soil	charcoal	-25	28270	180	32160	600	Muhs et al. (2001)
MORRISON, ILLINOIS LOESS SECTION									
WW-6524	IL-511.5	3.35, Peoria Silt	Succineidae		15555	40	18810	100	Pigati et al. (2015)
Aeon 2366	IL-526	10.5, Peoria Silt	Succineidae	-4.9	17770	150	21470	430	This study
Aeon 2365	IL-533	13.0, Peoria Silt	Succineidae	-4.4	19170	180	23080	470	This study
Aeon 2367	IL-536	14.5, Peoria Silt	Succineidae	-5.9	19730	110	23760	300	This study
WW-2155	IL-545	18.0, Farmdale Soil	humic acids	-25	31860	240	35730	530	Pigati et al. (2015)
IOWA TILL SAMPLES									
Beta-1764	Dows Quarry, Wright Co, IA	within till 3.2m above base of Sheldon Creek Fm.	wood		25390	1380	29450	2700	This study
Beta-2763	Brushy Creek, Webster Co., IA	within Sheldon Creek Fm. till	wood		25190	280	29310	690	This study
Beta-59952	Brushy Creek, Webster Co., IA	within Sheldon Creek Fm. till	wood		26580	280	30710	490	This study
Beta-10004	National Gypsum, Ft. Dodge, IA	within till, 2.3m above base of Sheldon Creek Fm.	wood		26620	520	30500	940	This study
Beta-2766	Brushy Creek, Webster Co., IA	within till, 1.2m above base of Sheldon Creek Fm.	wood		29310	430	33270	1000	This study

*Cal age = calibrated age. Calibrated ages were calculated using CALIB v. 7.1html, IntCal13.14C dataset; limit 50.0 calendar ka B.P. Calibrated ages are reported as the midpoint of the calibrated range. Probabilities for all age ranges as calculated by CALIB are 1.
Uncertainties are reported as the difference between the midpoint and either the upper or lower limit of the calibrated age range, whichever is greater.

minerals to outwash in the upper Mississippi River valley over the course of the last glacial period (Mudrey et al., 1982; Mickelson et al., 1983; Grimley, 2000; Catacosinos et al., 2001; Curry and Grimley, 2006; Jirsa et al., 2011), we hypothesize that K/Rb and K/Ba values in K-feldspars and/or micas could be effective discriminators of loess source sediments.

There are two purposes to the study presented here. The first is to test the hypothesis that K/Rb and K/Ba values may be effective discriminators of loess provenance. To do this, we present loess compositional data from a variety of regions in North America, where loess sources are distinctive, based on very different geologic settings. In principle, K/Rb and K/Ba should also be distinctive for loess derived from these diverse geologic terrains. If the hypothesis outlined in the first goal is validated, a second goal is to examine the K/Rb and K/Ba compositions of three thick, previously studied loess sections along the Mississippi River in Illinois (Fig. 3) to determine their sources, and to link these findings with Laurentide Ice Sheet history. Much more is now known about the glacial history of this region than at the time of the earliest loess research. Thus, it should be possible to correlate loess depositional history with advances of the various ice lobes of the Laurentide Ice Sheet.

2. Methods

Except for a section exposed near Mount Vernon, Indiana, all loess samples were acquired by drilling with a trailer-mounted, hydraulic drilling probe with a 1.5-m-long core barrel that has a diameter of 5.6 cm. Soils and sediments were described in the field using standard terminology as practiced in the USA (Birkeland, 1999). Materials collected for radiocarbon dating included wood, plant macrofossils, land snails and organic matter (for humic acid extractions). The land snails used for dating were all from the Succineidae family, which Pigati et al. (2010, 2013) have demonstrated yields reliable radiocarbon ages. All radiocarbon ages were calibrated to calendar ages using the IntCal13 dataset and CALIB 7.1 program (Stuiver and Reimer, 1993; Reimer et al., 2013). The ages reported in this study are presented in thousands of calibrated years before the present (YBP; 0 YBP = 1950 CE; ka = thousands of calibrated ^{14}C YBP), and uncertainties are given at the 95% (2σ) confidence level (Table 1).

For particle size analyses, conducted at the University of Iowa, samples were pretreated with hydrogen peroxide to destroy organic matter, acetic acid to remove carbonates, and sodium hexametaphosphate to enhance dispersion. Sand (particles with diameters >53 μm) was separated from silt and clay by wet sieving. Abundances of coarse silt (53–20 μm), fine silt (20–2 μm), and clay (<2 μm) were determined using settling and pipette analysis. The laboratory precision of the pipette analysis was routinely monitored with each suite of sample runs using analysis of an internal loess standard. Particle size analyses were also completed for selected samples using a Malvern laser particle size analyzer in the laboratories of the U.S. Geological Survey. The same pretreatments as for the wet-sieve and pipette analyses were used, except that HCl was utilized to remove any carbonates. For bulk mineralogy, samples were pulverized and homogenized in a shatterbox to a fine-silt size, and analyzed as random mounts using X-ray diffractometry (XRD). For clay mineralogy, samples were first pretreated by removal of organic matter with hydrogen peroxide and removal of carbonates with acetic acid, followed by addition of a sodium hexametaphosphate dispersant. Clays were isolated by settling and then mounted on glass slides by suction. Clay slides were X-rayed three times: air dried, after glycolation, and after heating at 550 °C for 1 h. In their studies of the mineral zones present in loess in Illinois, Frye et al. (1968) calculated clay mineral abundances as percentages, using weighted XRD peak height measurements. Hallberg et al. (1978, p. 8) outline their specific method of computation. We recognize that this approach yields measurements that are likely only rough approximations of actual weight percentages. Nevertheless, we employed this method in the present study in order to make our data as comparable to those of Frye et al. (1968) as possible.

Total carbonate mineral content was estimated using coulometric titration following the methods outlined in Engleman et al. (1985). This method determines the abundance of inorganic CO_2 in a sample and has good agreement with gasometric determinations of CO_2 content in a wide variety of geological materials. Determinations include the abundance of CO_2 that is present in both calcite and dolomite found in a sample, but without mineralogical differentiation. Hence, in calculating estimates of total carbonate mineral content, including both calcite [$CaCO_3$] and dolomite [$CaMg(CO_3)_2$], we consider this to be a "$CaCO_3$ equivalent" estimate.

Major element and trace element geochemistry was determined for pulverized splits of bulk samples using wavelength-dispersive X-ray fluorescence (XRF). This method generates an accurate and precise determination of all major elements, plus Rb and Ba. Both Rb and Ba are trace elements that follow K and are therefore found in K-feldspar and mica (see Muhs, 2017 for a more detailed review of this topic). Because of its ion size, Ba is also found in plagioclase feldspar. Due to its higher charge, however, Ba is typically captured by K-bearing minerals, and its concentrations in K-feldspar are therefore usually much higher than in plagioclase (Mason and Moore, 1982). Therefore, bulk analyses of K, as well as Rb and Ba, will typically reflect K-feldspar compositions, and, to a lesser extent, mica compositions. We note that although wavelength-dispersive XRF was employed in the present study for the determination of K, Rb, Ba and other elements, the earlier studies of Muhs (2017) and Muhs et al. (2008a, 2013, 2017) used energy-dispersive XRF for the determination of K, Rb, and Ba concentrations. Comparative studies we conducted showed that while concentrations of Rb and Ba measured using the two methods show no significant differences, there can be slight differences in the concentrations of K (see discussion in Muhs [2017] and Muhs et al., [2017]). Thus, readers should be aware that K concentration data presented here may not be directly comparable with the energy-dispersive XRF data reported in earlier studies. All field measurements, locality coordinates, and laboratory data are given in Supplementary Data Tables 1–8.

3. Loess stratigraphy in the Mississippi River drainage basin of central North America

More than a century of study has yielded much information about the Quaternary stratigraphy of loess in central North America (Fig. 4). In summarizing the Pleistocene loess record here, we follow the stratigraphic terminology outlined in Willman and Frye (1970). In central North America, including the Mississippi River valley, the oldest widespread eolian silt is called Loveland Silt (in Illinois) or Loveland Loess (elsewhere), although older loesses have been observed below this unit in the region (McKay, 1979b; Markewich et al., 1998; Grimley et al., 2003; Mason et al., 2007; Jacobs and Davis, 2018). Loveland Loess is found in eastern Nebraska and Kansas, across western Iowa, and along the eastern side of the Mississippi River, from Wisconsin to at least the state of Mississippi (Fig. 2), based on studies by Frye et al. (1968), Ruhe (1969), Bettis (1990), Leigh and Knox (1994), Grimley et al. (2003), Rutledge et al. (1996), Mason et al. (2007) and Markewich et al. (2011). Luminescence ages reported by Brown and Forman (2012) indicate that Loveland Loess along the Missouri River could have been deposited between ~190 ka and ~130 ka, and along the lower Mississippi River valley between ~184 ka and ~122 ka (Markewich et al., 2011), correlating this sediment with Marine Isotope Stage (MIS) 6, using the chronology of Martinson et al. (1987). The Sangamon Soil is developed in Loveland Silt/Loess, or in till that is thought to date to the penultimate (Illinoian Stage, or MIS 6) glacial period. At well-drained sites, this distinctive, clay-rich, reddish-brown paleosol likely formed during much or all of MIS 5 and part of MIS 4 (Fig. 4). The thin loess found above the Sangamon Soil is called Roxana Silt (correlative with Pisgah Formation loess in western Iowa and Gilman Canyon Formation loess in Nebraska) and correlates temporally with MIS 3. Optically stimulated luminescence (OSL) ages of Pisgah Formation loess/Roxana Silt along the Missouri River in western Iowa range from ~46 ka to ~31 ka (Muhs et al., 2013). Luminescence ages of ~56 ka to ~34 ka have been reported for Roxana Silt in the lower Mississippi River valley (Markewich et al., 2011). Between the Wabash and Ohio Rivers (Fig. 2), Roxana Silt has been dated to at least ~42 ka and may consist of two units separated by a paleosol (see discussion below). In the upper Mississippi River drainage basin, calibrated radiocarbon ages indicate that Roxana Silt accumulated between about ~55 ka and ~29 ka (Leigh and Knox, 1993). The Farmdale Soil developed in the upper part of Roxana Silt (Fig. 4).

The thickest eolian silt of the Late Quaternary, resting on the Farmdale Soil, is called Peoria Silt (in Illinois) or Peoria Loess (elsewhere). Many radiocarbon ages and OSL ages (see reviews in McKay [1979a], Grimley et al., [1998], Bettis et al., [2003], Muhs et al., [2008a], Muhs [2013], Pigati et al., [2015], and Nash et al., [2018]) indicate that Peoria Loess, across the Great Plains, along the Missouri River, and all along the Illinois and Mississippi rivers (Figs. 2 and 3), was deposited during the last glacial period (late Wisconsin), from around ~29–25 ka to ~17–15 ka (cal yr) or equivalent to MIS 2 of the oxygen isotope record (Fig. 4). The modern surface soils of the region developed in the upper part of Peoria Loess primarily during the Holocene, or MIS 1.

Throughout the mid-continental region, loess thickness and particle size trends show that paleowinds transporting silt that accumulated as Peoria Loess were westerly or northwesterly (see summary in Muhs and Bettis, 2000). Specifically in the state of Illinois (Fig. 3), where much of the loess of the upper Mississippi

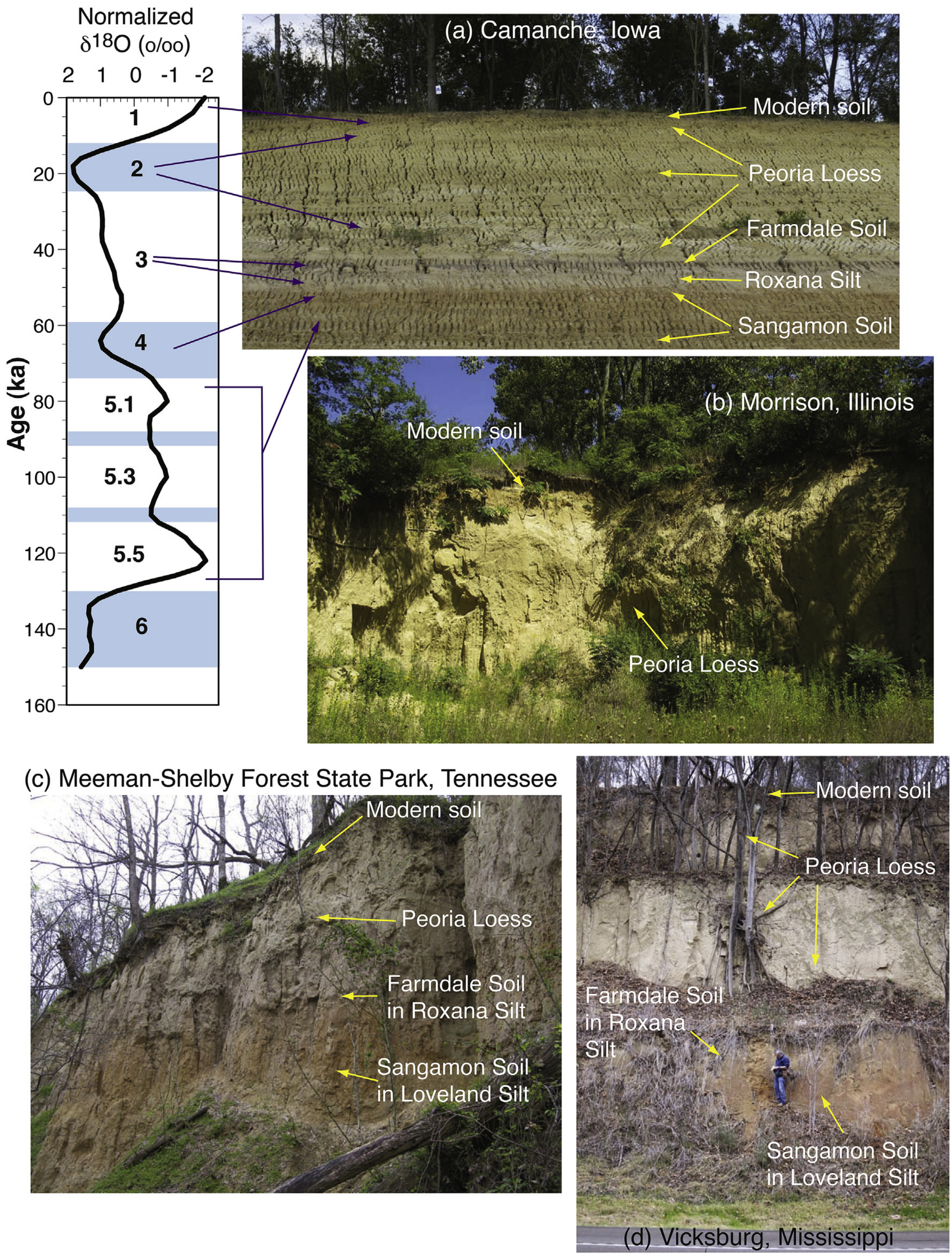

Fig. 4. Late Quaternary loess stratigraphy in the Mississippi River valley. (a) Photograph of loess section near Camanche, Iowa (see Fig. 5 for location) showing principal late Quaternary loess units and correlation with the deep-sea oxygen isotope record of Martinson et al. (1987). Bold numbers on oxygen isotope curve are stages; glacial periods are shaded blue. Peoria Loess in the photograph is ~4 m thick. (b) Modern soil and upper Peoria Loess exposed in a quarry at Morrison, Illinois (see Figs. 2 and 3 for location). (c) Modern soil, Peoria Loess, Farmdale Soil and Sangamon Soil exposed along bluffs north of Memphis, Tennessee, in Meeman-Shelby Forest State Park (see Pigati et al., 2015, for details on location). (d) Modern soil, Peoria Loess, Farmdale Soil and Sangamon Soil exposed along the highway east of Vicksburg, Mississippi (see Pigati et al., 2015, for details on location). All photographs by D.R. Muhs except for (d), which is courtesy of John Aleinikoff, U.S. Geological Survey. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

River Basin is located, detailed studies of loess thickness and particle size have also shown that paleowinds were westerly and/or northwesterly during the time of Peoria Loess accumulation (Smith, 1942; Frazee et al., 1970).

4. Results

4.1. K/Rb and K/Ba in different loess regions of North America

Loess bodies in different parts of North America are derived from highly contrasting types of bedrock. In Alaska, loess is derived from glacial till and outwash, in turn derived from metamorphic rocks, many with mafic protoliths, along with smaller amounts of granitic and volcanic rocks (Muhs and Budahn, 2006; Muhs et al., 2018). In the Great Plains region, loess is derived from a mix of felsic, volcaniclastic siltstone and fluvial sediments eroded from diverse crystalline rocks, the latter from mountains to the west (Aleinikoff et al., 1999, 2008; Yang et al., 2017). Loess of the Mississippi River valley region is derived from glacial till and outwash containing particles eroded from Precambrian crystalline rocks (granites and metamorphic rocks), Paleozoic shales, dolomites, and limestones, and Cretaceous shales (Fig. 5). For our comparisons of K/Rb and K/Ba compositions from different parts of North America, we utilized late Quaternary loess from regions that have contrasting source rocks. The loess bodies in this comparison include: (1) Peoria Loess in the Great Plains (Figs. 1, 2 and 5) from a core drilled near Fort Morgan in eastern Colorado (see location in Muhs et al., 2008a, their Fig. 2); (2) loess from the early and late stages of the last glacial period near Jackson Hole, Wyoming, the easternmost portion of the Snake River Plain loess area shown in Figs. 1 and 5 (see Pierce et al., 2011); (3) Peoria Loess from the Great Plains collected throughout Nebraska (Fig. 2; see Muhs et al., 2008a for specific localities); (4) Peoria Loess from the easternmost part of the greater Mississippi River valley loess region (Figs. 1, 2 and 5) of central Ohio (Rutledge et al., 1975a; b); (5) Alaskan loess (Fig. 1) of late, last-glacial age from the Kenai Peninsula in the southern part of the region (Muhs et al., 2000); (6) Late Quaternary loess from Fairbanks, along the Tanana River in central Alaska (see Muhs et al., 2003, 2008b); and (7) last-glacial-aged loess from the Yukon-Tanana Upland of central Alaska (Muhs et al., 2018). However, loesses from two other key regions, one to the west of Illinois (central and eastern Iowa) and one to the east of Illinois (southern Indiana), are not as well documented. Thus, we provide information on these two areas here.

4.1.1. Background: loess stratigraphy in eastern Iowa and southern Indiana

In central and eastern Iowa, Peoria Loess was collected from short cores via drilling at five localities and a quarry exposure at a sixth locality (Figs. 6 and 7). Because loess is relatively thin (~3–5 m) in this part of Iowa, we encountered the easily recognizable Farmdale Soil and Sangamon Soil at three localities. The Sangamon Soil, where we encountered it, has a light olive brown (2.5Y 5/3, moist), clay loam Btg horizon (where poorly drained) or a grayish brown (10YR 4/2, moist) or dark grayish brown (10YR 5/2, moist), silty clay loam Bt horizon, the latter with strong fine angular blocky structure and almost continuous clay films on ped faces. The Farmdale Soil occurs above the Sangamon Soil and is a dark or very dark grayish brown (10YR 4/2 or 2.5Y 3/2, moist), leached, massive, silt loam or silty clay loam, and consists only of a buried A horizon. Above the Farmdale Soil, Peoria Loess is massive and characterized by yellowish-brown (10YR 5/4, moist) or grayish brown (2.5Y 5/2, moist) colors with silt loam textures. All sites that we examined are apparently not eroded, as they all host well-developed soils with A/Bt/BC/C or A/Bt/C profiles. The Bt horizons of the modern soils at these sites have subangular blocky structure with clay films on ped faces. The westernmost exposure, at Earlham, Iowa, has radiocarbon ages from the uppermost part of the Farmdale Soil (Woida and Thompson, 1993) of ~26.9–25.6 ka (in calibrated radiocarbon years) that provide maximum-limiting ages for the earliest Peoria Loess accumulation here. Radiocarbon ages (calibrated) on wood from the uppermost Peoria Loess elsewhere in central Iowa are ~17.5–17.2 ka (Bettis et al., 1996). Thus, we consider loess collected in central and eastern Iowa to have been deposited largely between ~25 ka and ~17 ka. K/Rb and K/Ba analyses were conducted on unaltered Peoria Loess samples collected from these six profiles (Fig. 7).

In order to make comparisons with loess that was most likely derived from sources to the east of the Mississippi River, we studied a thick Peoria Loess section near Mount Vernon, in southern Indiana, to the southeast of the Wabash River and north of the Ohio River (Figs. 2 and 3). Ruhe and Olson (1980) and Hayward and Lowell (1993) previously studied this section. Bettis et al. (2003) reported two maximum-limiting radiocarbon ages for Peoria Loess from the section at Mount Vernon, and Pigati et al. (2015) recently reported additional radiocarbon ages throughout the section.

Although the surface soil is eroded, the Mount Vernon section records a remarkable portion of the late Quaternary (Fig. 8). The base of the section hosts a paleosol ~1.5 m thick that is likely the equivalent of the "Yarmouth Soil" that has been recognized elsewhere in the greater Mississippi River valley (see Grimley et al., 2003; Markewich et al., 2011). The Yarmouth Soil here has likely developed in a mix of loess and colluvium. This paleosol has an E horizon ~14 cm thick and an argillic Bt horizon that is nearly a meter thick. The Yarmouth Soil is overlain by Loveland Silt (MIS 6), a loess that is ~58 cm thick, pink (7.5YR 7/4, dry), massive, and with a silt loam texture. The Sangamon Soil of the last interglacial period (MIS 5 and part of MIS 4) is developed in Loveland Silt. This paleosol still retains a pink (7.5YR 7/4, dry) E horizon ~28 cm thick, with moderate, medium, subangular blocky structure. Below the E horizon of the Sangamon Soil, there is a well-developed, yellowish-red (5YR 5/6, dry) to reddish-yellow (7.5YR 6/6 or 7/6, dry) or strong brown (7.5YR 5/8, dry) argillic Bt horizon that is ~74 cm thick. The upper Bt horizon of the Sangamon Soil has weak, coarse, prismatic structure parting to strong, medium-to-fine, angular blocky structure with common, nearly continuous clay films on ped faces. The lower part of the Bt horizon has weak-to-moderate, medium-to-coarse, subangular blocky structure with discontinuous clay films on ped faces.

The Sangamon Soil is overlain by two paleosols that are developed in loess that is correlated to the Roxana Silt of the greater Mississippi River valley. The lower paleosol is ~60 cm thick, has a silt loam texture, pink (7.5YR 7/4, dry) colors, moderate fine-to-medium subangular blocky structure, and hosts fossil land snails and krotovina.

We refer to this simply as the "Lower" paleosol. Charcoal from this paleosol has a calibrated radiocarbon age of ~41.3 ka, which we interpret as a minimum age (Table 1). The "Lower Paleosol" is overlain by ~1.2 m of Roxana Silt (massive, very pale brown, 10YR 7/4, dry) and the younger paleosol, with only an A/C profile, is the Farmdale Soil developed in the upper 60 cm of this loess. This paleosol has silt loam textures throughout, yellowish-brown (10YR 5/4, dry) to pale brown (10YR 6/3, dry) colors, and weak, medium-to-fine subangular blocky structure. Land snails of the Succineidae family are abundant in this paleosol and yielded a calibrated radiocarbon age of ~30.7 ka (Pigati et al., 2015).

At least 13 m of Peoria Silt accumulated above the Farmdale Soil at Mount Vernon. This loess is massive, and has very pale brown (10YR 7/4 or 7/3, dry) to brownish-yellow (10YR 6/6, dry) or yellow

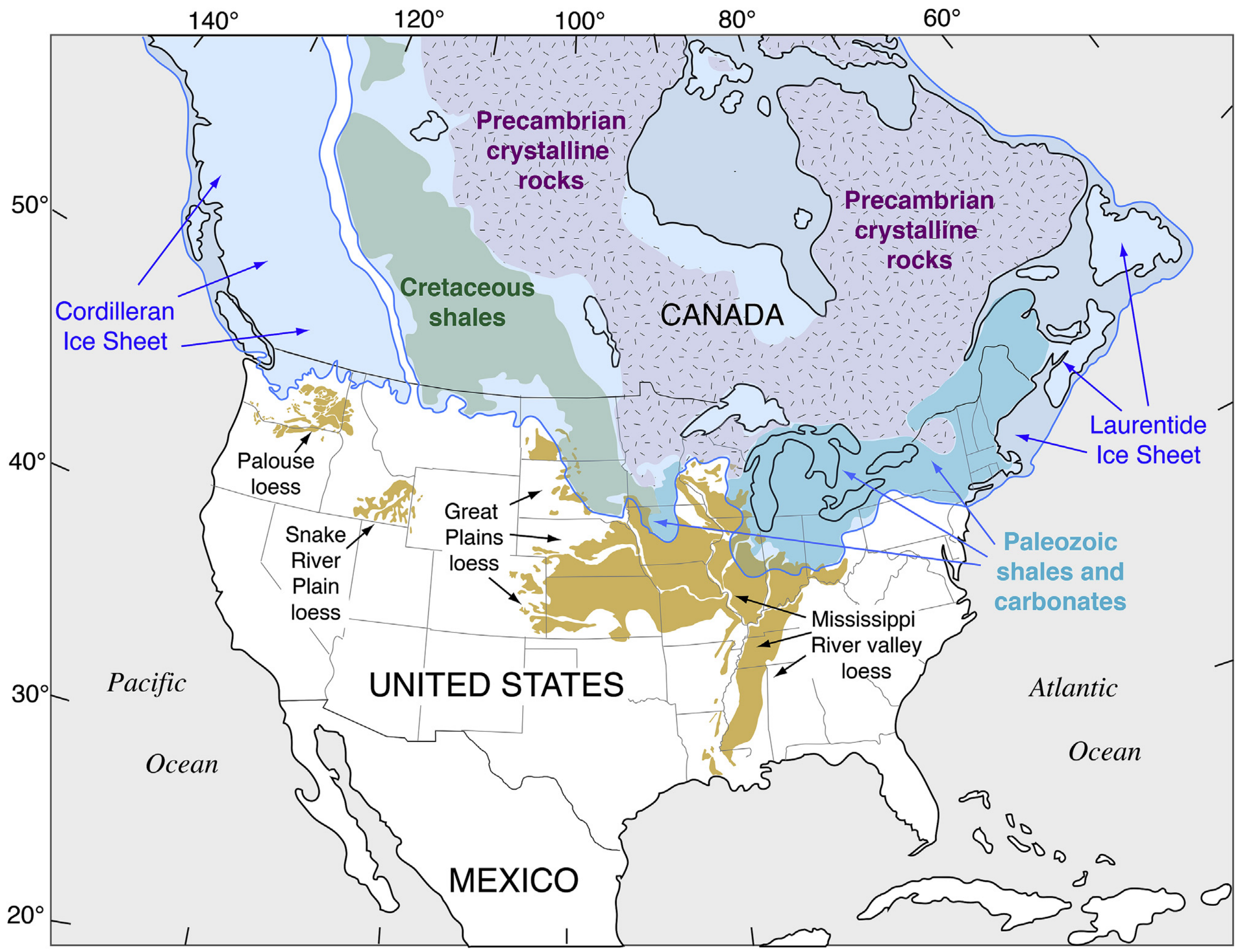

Fig. 5. Map showing principal bedrock types in North America that were eroded by the Laurentide Ice Sheet during the last glacial period. Bedrock is highly generalized from Reed et al. (2005). Extent of ice sheets at the last glacial period is taken from Dyke et al. (2002); loess distribution from sources given in Fig. 1 and 2.

(10YR 7/6) colors, with silt loam textures. Land snails of the Succineidae family are found at various depths in this loess. Calibrated radiocarbon ages of snails (Table 1) indicate that Peoria Loess deposition began at ~29–28 ka and continued until some time after ~23 ka (Pigati et al., 2015). Although we observed no morphological evidence of paleosols within Peoria Loess, at two depth intervals (5.5–6.5 m and 9.5–11 m), there is geochemical evidence that loess deposition could have slowed to the point where minor syndepositional mineral weathering may have taken place (see discussion below). In contrast, higher in the section, the similarity of ages (~24–23 ka) for snails at depths of 3.3 m and 5.8 m permits an interpretation that loess accumulation later could have been very rapid. Bulk mineralogy from XRD analyses indicates that the major minerals in Peoria Loess at Mount Vernon are quartz, plagioclase, K-feldspar, dolomite, and calcite, with smaller amounts of mica and amphibole, likely hornblende. Of the two carbonate minerals, dolomite is far more abundant than calcite. Although the modern soil at the main section sampled at Mount Vernon is eroded, we described and sampled a nearby, stable site that has a modern soil of the Alford series developed in the uppermost part of Peoria Loess. This soil is ~1.5 m thick with an A/E/Bt/BC/C profile, a typical Alfisol of the sort developed under forest in the region.

The paleosols and modern soil at Mount Vernon show evidence of significant mineral alteration by chemical weathering, which can be assessed using major element concentrations or major element ratios (see examples in Birkeland, 1999). Carbonate mineral (dolomite plus calcite) abundance is shown by measurements of total $CaCO_3$ content and the sum of weight-percentages of CaO, MgO, and LOI (LOI = loss on ignition). The latter sum will always be somewhat greater than total $CaCO_3$ content, because there are small contributions from other Ca-bearing and Mg-bearing minerals. Plagioclase depletion is proxied by Na_2O/TiO_2 and apatite depletion is proxied by P_2O_5/TiO_2. Modern and buried soils at Mount Vernon show evidence of significant carbonate mineral, plagioclase and apatite depletion (Fig. 8). Between the modern soil and the Farmdale Soil, Peoria Loess is mostly unaltered, although there is evidence of possible carbonate depletion (lower $CaCO_3$ and CaO + MgO + LOI values), slight plagioclase depletion (lower Na_2O/TiO_2 values), and slight apatite depletion (P_2O_5/TiO_2 values), at depths of 5.5–6.5 m and 9.5–11.0 m. The geochemical evidence for carbonate mineral depletion is supported by XRD analyses that show relatively lower abundances of dolomite in these two depth intervals. K/Rb and K/Ba analyses were conducted on samples from the ~13 m of Peoria Loess in this section, excluding the depth intervals from 5.5 to 6.5 m and 9.5–11.0 m where there is evidence of possible mineral alteration.

4.1.2. Test case #1: K/Rb and K/Ba values in loess of central and eastern Iowa versus loess of southern Indiana

Peoria Loess in central and eastern Iowa is considered to have

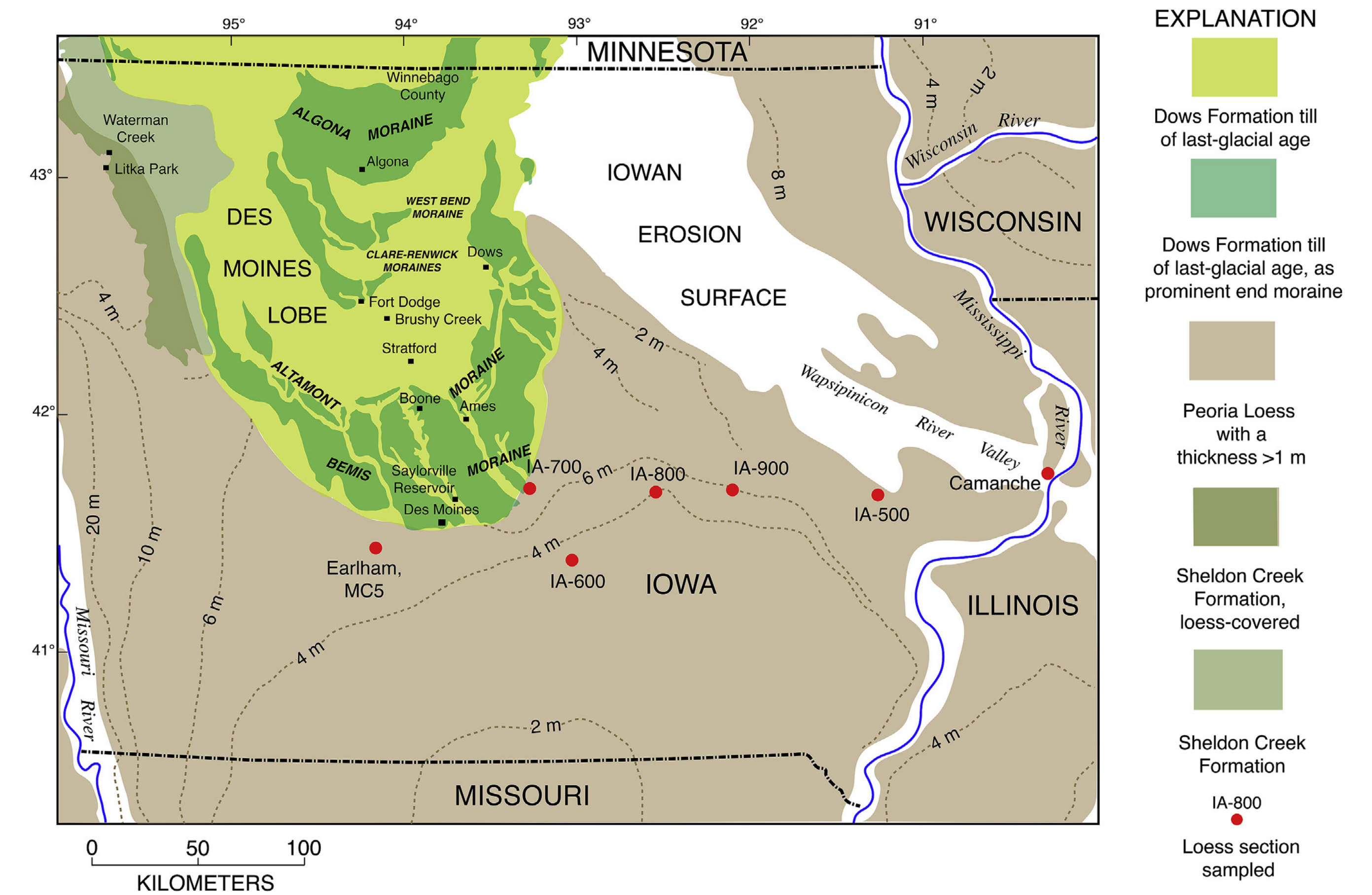

Fig. 6. Distribution of loess and loess thickness contours in most of Iowa and parts of adjacent states, and location (in green shades) of late Wisconsin (last glacial) Dows Formation (till) of the last glacial age Des Moines Lobe of the Laurentide Ice Sheet, as well as a slightly older, last-glacial-age underlying unit (Sheldon Creek Formation, formerly referred to as "Tazewell" till). Redrawn from Hallberg et al. (1991). Note that recent work has also revealed the presence of the Sheldon Creek Formation till to the *east* of the mapped extent of the Dows Formation shown here (Kerr et al., 2017). Also shown are locations of loess sections sampled (shown in Fig. 7). Place names shown on the Des Moines Lobe are key radiocarbon localities shown in Fig. 26a; other place names are referred to in the text. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

derived much of its sediment from outwash, in turn derived primarily from till of the last-glacial-aged Des Moines Lobe, based on loess distribution and thickness contours (Fig. 6), as well as its mineralogical composition. Till of the Des Moines Lobe, called the Dows Formation (Bettis et al., 1996), was derived from Cretaceous shale, Paleozoic carbonate rocks and Precambrian crystalline rocks (Hallberg and Kemmis, 1986; see also Fig. 5). Thus, the Dows Formation is characterized by relatively high (56–74%) amounts of smectite in the clay fraction, and moderate amounts of calcite and dolomite (total carbonate contents of 14–22%) in bulk samples (Kemmis et al., 1981). Loess in central and eastern Iowa also contains high quantities of smectite, as well as moderate quantities of calcite and dolomite (see Table 3 of Hallberg et al., [1978] and Tables 36 and 41 of Hallberg [1980]). The elements K, Rb and Ba in the tills of the Des Moines Lobe are probably found largely in K-feldspar and mica, derived from Precambrian crystalline rocks over which the ice traversed, largely in Minnesota and adjacent southern Canada, as well as some detrital K-feldspar and mica in Cretaceous shale. To test the idea that loess from central and eastern Iowa is derived primarily from the till of the Des Moines Lobe, we compared K/Rb and K/Ba values in Iowa loess to the same element ratios in the <63 μm fraction of tills from the Des Moines Lobe and the Superior and Rainy lobes (Fig. 2), sampled and analyzed in Minnesota by Lively and Thorleifson (2009). Results show that tills from the two northern lobes have distinctive compositions, and that central and eastern Iowa loess compositions fall within, or close to, the range for Des Moines Lobe till (Fig. 9a).

The immediate source of loess at Mount Vernon and elsewhere in southwestern Indiana (Figs. 2 and 3) was likely outwash in the Wabash River valley (Fehrenbacher et al., 1965a; b; Ruhe and Olson, 1980). In southwestern Indiana, near Mount Vernon, loess thickness contours parallel the Wabash River, and thicknesses decrease from ~7 m or more near the river to ~2 m over a distance of ~10 km (Fehrenbacher et al., 1965a, their Fig. 1). This implies loess derivation primarily from the west, where the Wabash River is situated. There were also possibly some contributions from the nearby Ohio River. Outwash in the valleys of these rivers in turn would have been derived from Laurentide Ice Sheet tills from the Lake Ontario-Erie Lobe, the Huron Lobe, the Saginaw Lobe, and probably the Lake Michigan Lobe (Fig. 2). Ice in these lobes traversed terrains with mica-rich, Paleozoic shale as well as Paleozoic dolomite and limestone (Mickelson et al., 1983; Grimley, 2000; see Fig. 5). Thus, compared to central and eastern Iowa, loess in southern Indiana has far lower smectite and much higher (~50–60%) mica contents, as well as higher (~25–40%) carbonate mineral contents (Fehrenbacher et al., 1965b; Ruhe and Olson, 1980). In tills from the Lake Michigan, Saginaw, and Lake Huron lobes, K, Rb and Ba are likely derived in part from K-feldspar and mica from different

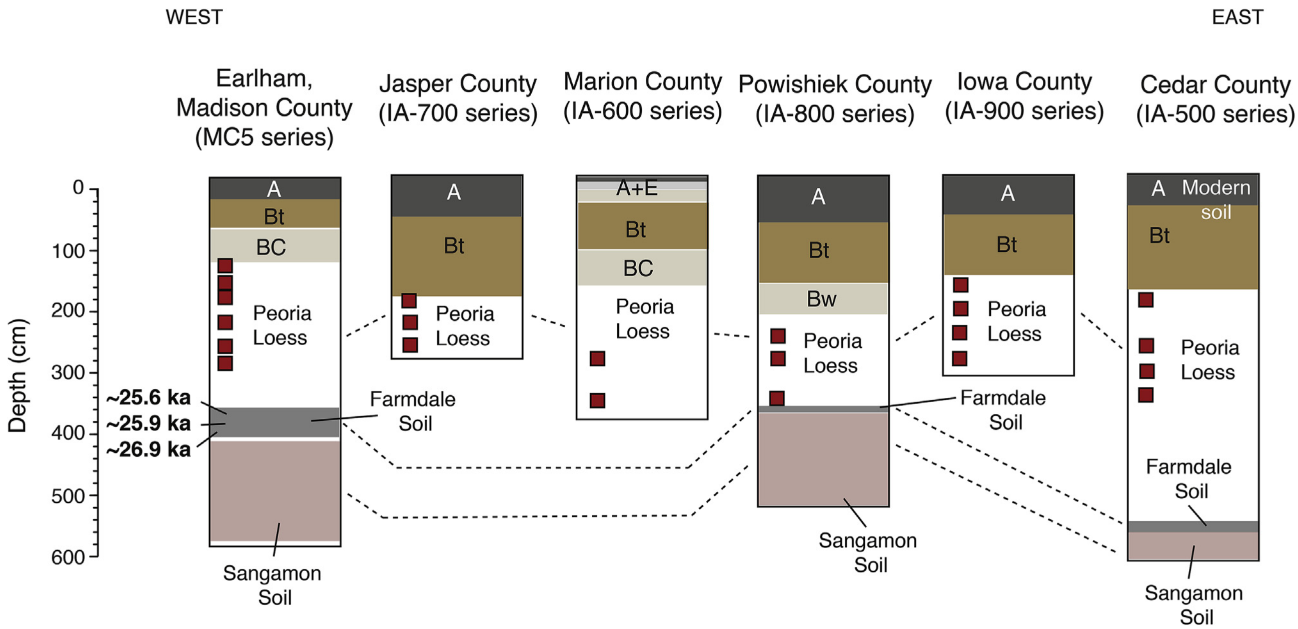

Fig. 7. Stratigraphy of loess sections shown in Fig. 6 sampled by the drilling in central and eastern Iowa. Stratigraphy for all sections is by the authors, except for the Earlham locality, which is simplified from Woida and Thompson (1993). Red squares show locations of Peoria Loess samples analyzed for geochemistry, as shown in Fig. 9. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

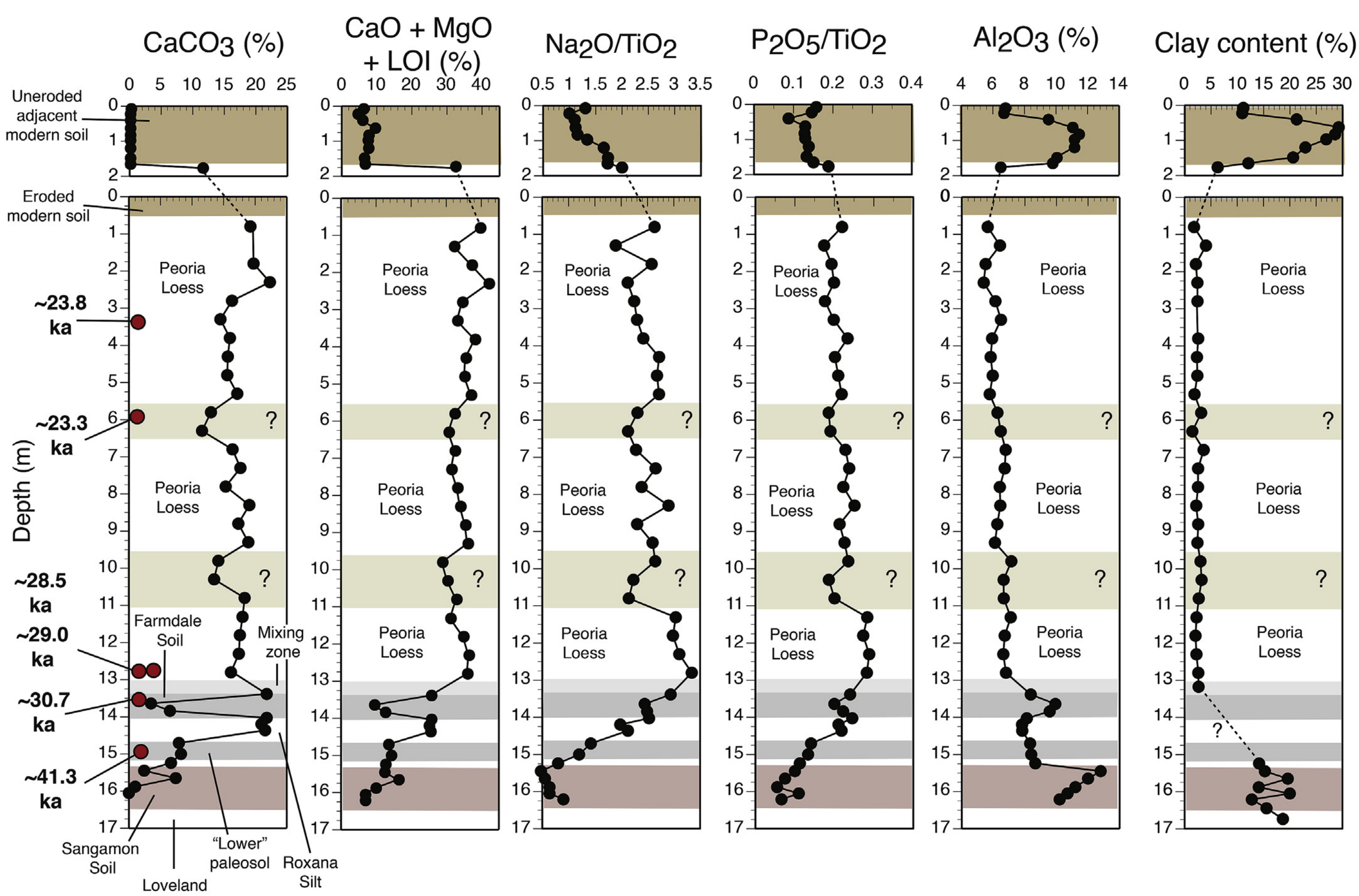

Fig. 8. Stratigraphy of loess section near Mount Vernon, Indiana and physical and chemical variations as a function of depth. Stratigraphy by the authors; calibrated radiocarbon ages are from Pigati et al. (2015), except for the lowest calibrated age of ~41.3 ka at ~15 m depth, charcoal in the lower Farmdale Soil, which is from the present study (USGS #WW-7115, uncalibrated age of 37,060 ± 870 yr, courtesy of J.P. McGeehin, U.S. Geological Survey; see Table 1). Possible intra-Peoria paleosols, based on geochemical data, are shown as light brown shades with queries. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

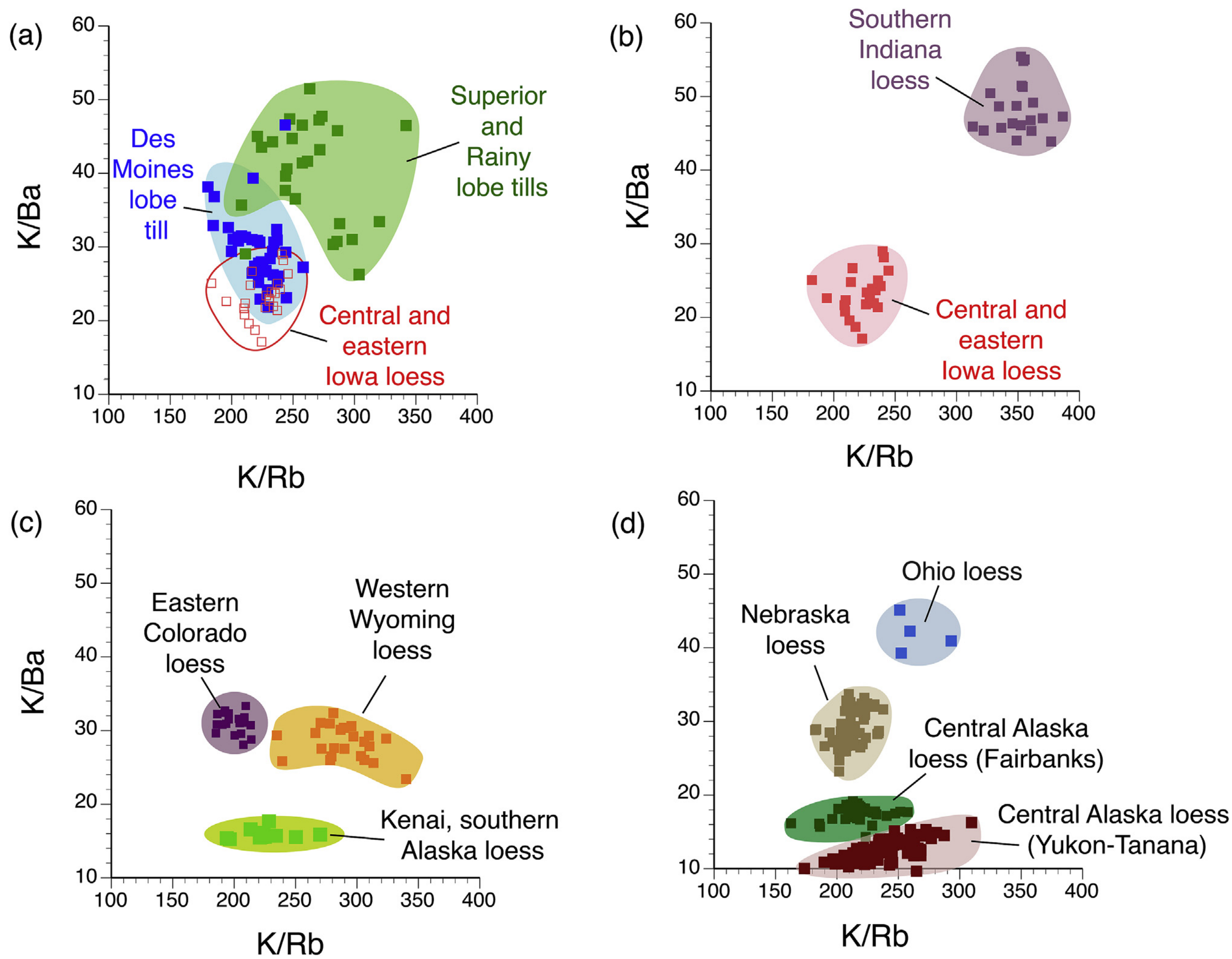

Fig. 9. (a) K/Rb and K/Ba compositions in Peoria Loess from eastern and central Iowa (open red squares; see Fig. 6 for locations) compared to ranges of these values in the <63 μm fraction of glacial till collected from the Des Moines Lobe and Superior and Rainy Lobes in Minnesota (Fig. 2). Iowa loess data are from the present study; Minnesota till data are from Lively and Thorleifson (2009). Note that analytical methods used by Lively and Thorleifson (2009) differ from those used in the present study. (b) K/Rb and K/Ba compositions in Peoria Loess from the same locations as in (a) for eastern and central Iowa loess (filled red squares); southern Indiana loess (filled purple squares) is from Mount Vernon, Indiana (Fig. 2). (c) K/Rb and K/Ba compositions from Peoria Loess in eastern Colorado (Fort Morgan, Colorado; see Muhs et al., [2008a] for locality), last-glacial-age loess from Jackson Hole, western Wyoming (see Pierce et al., [2011] for locality), and late, last-glacial loess from the Kenai Peninsula of southern Alaska (see Muhs et al., [2000] for localities). (d) K/Rb and K/Ba compositions in Pleistocene loess from the Chena Hot Springs Road section near Fairbanks, Alaska (see Muhs et al., [2003] for location), last-glacial loess from the Yukon-Tanana Upland of central Alaska (see Muhs et al., [2018] for location), Peoria Loess from Nebraska (see Muhs et al., [2008a] for locations), and Peoria Loess from Ohio (see Rutledge et al., [1975a, 1975b] for location). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Precambrian crystalline rocks over which these eastern lobes of ice traversed, largely in Wisconsin, Michigan, and adjacent parts of Canada, as well as mica from Paleozoic shale. Regrettably, unlike the case for eastern and central Iowa, we have no data on the K/Rb and K/Ba compositions of Lake Michigan, Saginaw, and Lake Huron Lobe tills.

Results for central/eastern Iowa loess and southern Indiana loess are consistent with previous studies that have characterized the very different compositions of these two eolian silt bodies. Measurements of carbonate mineral contents in the two loess bodies (here represented by CaO + MgO + LOI) are very different, with significantly higher carbonate contents, mostly dolomite (see Fehrenbacher et al., [1965b]), in southern Indiana loess (30–40%) compared to Iowa loess (5–17%). The contrasting source sediments for loesses in the two regions are also reflected in very different K/Rb and K/Ba values, both of which are much higher in southern Indiana loess (Fig. 9b).

4.1.3. Test case #2: K/Rb and K/Ba in loess from diverse geologic terrains in North America

As additional tests, we analyzed late Quaternary loess collected from geologically diverse terrains elsewhere in North America. Results indicate that loess compositions with regard to K/Rb and K/Ba are distinctive in these different regions (Fig. 9c and d). Eastern Colorado and western Wyoming loess bodies have similar K/Ba values, but different K/Rb values. Southern Alaska loess overlaps the K/Rb values of Colorado and Wyoming loess, but has much lower K/Ba values. Nebraska loess and central Alaskan loess have overlapping K/Rb values, but different K/Ba values. Loess in Ohio has higher K/Ba values than all other regions, with the exception of Indiana (Fig. 9b,d). In central Alaska, loess at Fairbanks, near the Tanana River, has a composition that is distinctive from loess of the Yukon-Tanana Upland, also in central Alaska, but close to the Yukon River (Fig. 9d). We conclude from these comparisons that K/Rb and K/Ba are effective discriminators for loess derived from diverse geologic terrains.

It is also important to document the fact that loess bodies that are known to have the same source, based on independent lines of evidence, show similar K/Rb and K/Ba values. Here we use examples from eastern Colorado and Nebraska. Aleinikoff et al. (1999), using the Pb-isotopic compositions of K-feldspars and U-Pb age distributions in detrital zircons, showed that in eastern Colorado, some loess is derived from the South Platte River, but much of it is derived from volcaniclastic siltstone of the Tertiary White River Group. Using the same methods, Aleinikoff et al. (2008) demonstrated that, while some loess in Nebraska is derived from the Platte River or the Missouri River, the majority of loess in this region, like that in eastern Colorado, is also derived from the White River Group. From this, it can be hypothesized that K/Rb and K/Ba values should be similar for eastern Colorado and Nebraska loesses. Results confirm that there is no significant difference in these ratios for the two loess bodies (Fig. 9c and d).

4.1.4. Test case #3: K/Rb and K/Ba as a function of loess particle size and the effects of pedogenesis

Because particle size distribution in loess changes as a function of distance downwind from a source (see examples in Ruhe, 1969, 1983 and Muhs, 2013) and with wind intensity, it is pertinent to ask whether K/Rb and K/Ba values might vary with differing particle sizes, due to changes in mineralogy. Chinese loess, for example, has varying proportions of feldspar and mica depending on particle size class (Eden et al., 1994). Because K-feldspar and mica accommodate different proportions of K, Rb and Ba (Heier and Adams, 1964; Lange et al., 1966; Mason and Moore, 1982), it might be expected that K/Rb and K/Ba values could change as a function of particle size class. To test this, we computed K/Rb and K/Ba values from K, Rb and Ba concentrations given in Yang et al. (2006), who reported these data for different particle size classes in Chinese loess. Their analyses were also conducted using XRF methods, and thus their data are directly comparable to those in the present study. Results of these computations indicate that last-glacial loess ("L1" loess in Chinese loess stratigraphic nomenclature) has K/Rb and K/Ba values that are not significantly different across six particle size classes, ranging from clay to sand (Fig. 10a and b). In addition, K/Rb and K/Ba values do not differ significantly in different particle size classes for the last interglacial soil ("S1" soil) developed in the penultimate glacial loess ("L2" loess; Fig. 10c and d).

4.2. Upper Mississippi River valley: stratigraphy, mineralogy and geochemistry of loess sections

Having established that K/Rb and K/Ba values are effective

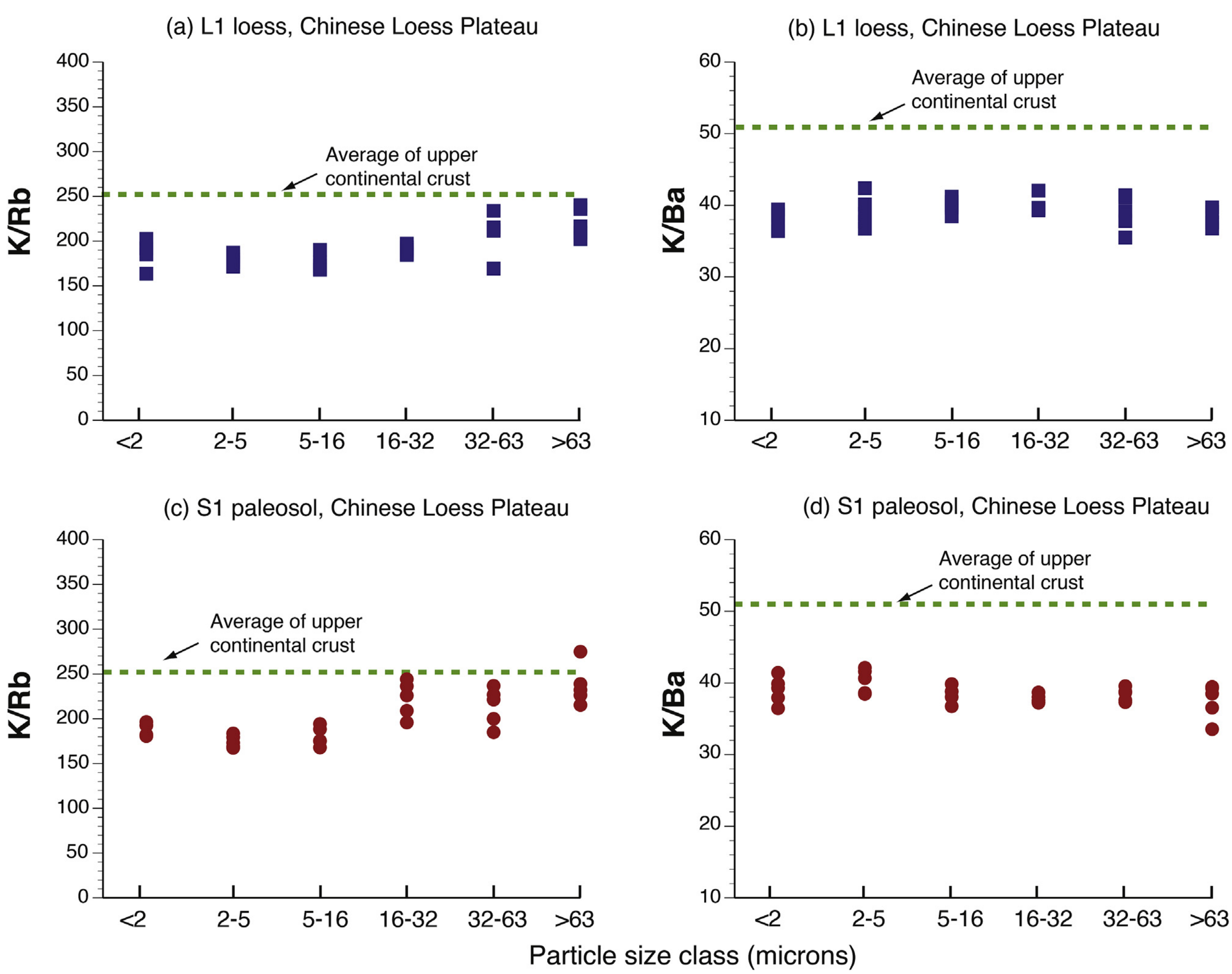

Fig. 10. K/Rb and K/Ba compositions in loess (L1 or last-glacial age) and paleosols (S1, or last interglacial age) shown as a function of particle size class, from the Chinese Loess Plateau. Calculations are by the authors from data in Yang et al. (2006). Composition of average upper continental crust calculated by the authors from data in Taylor and McLennan (1985; their Table 2.15).

discriminators of loess provenance, we examined three late Quaternary loess sections in the upper Mississippi River valley region of Illinois (Figs. 2 and 3). All three sections have been shown to have distinct mineral zones within relatively thick last glacial period (MIS 2) Peoria Loess, based on studies by previous investigators. Frye et al. (1968) studied two of the sections located in northern Illinois, Morrison and Rapids City, and McKay (1977) studied the Morrison section. A third locality, Greenbay Hollow, studied by Grimley et al. (1998), is found between the Mississippi and Illinois River valleys in central Illinois.

4.2.1. Morrison, Illinois

The Morrison locality is situated on the dissected uplands covered with thick loess east of the Mississippi River and north of the Rock River (Fig. 11). As noted earlier, loess thickness trends (Fig. 3) indicate that paleowinds at the time of loess deposition were dominantly from the west and/or northwest. The landscape around Morrison is adjacent to the remarkable “paha” topography of northwestern Illinois. Pahas in northwestern Illinois are long, narrow hills, composed of loess and intercalated aeolian sand, with long axes that are oriented northwest-to-southeast. One interpretation is that they are erosional remnants (Willman and Frye, 1970), and, given their morphology, this would mean that they are essentially yardangs that developed *after* loess deposition. An alternative interpretation, and one that we favor, is that they are loess dunes (Flemal et al., 1972), perhaps analogous to the parna dunes of Australia (Dare-Edwards, 1984). More work is needed on the origin of these landforms, but either interpretation implies northwesterly paleowinds, in agreement with loess thickness trends (diminishing to the east) in this part of Illinois (Fig. 3).

During the last glacial period, outwash deposits, now well above the modern floodplain, accumulated to form what has been called the Savanna Terrace along the Mississippi River valley (Flock, 1983; Bettis and Hallberg, 1985; Bettis and Hajic, 1990; Knox, 1996; Bettis et al., 2008). Remnants of this terrace along the modern Mississippi River west of Morrison are shown in Fig. 11, based on mapping by Anderson and Miao (2013). Calibrated radiocarbon ages of Savanna Terrace sediments in nearby northeastern Iowa, reported by Bettis and Hallberg (1985) and Bettis and Hajic (1990), range from ~22.4 ka to ~19.5 ka. A younger terrace inset against the Savanna Terrace has a calibrated radiocarbon age of ~15 ka (Bettis and Hallberg, 1985). Thus, accumulation of last-glacial-aged outwash sediments in the Mississippi River valley probably began before ~22 ka and aggradation apparently continued until ~15 ka, as summarized by Bettis et al. (2008). These sediments were the most likely immediate source of loess in the Morrison section.

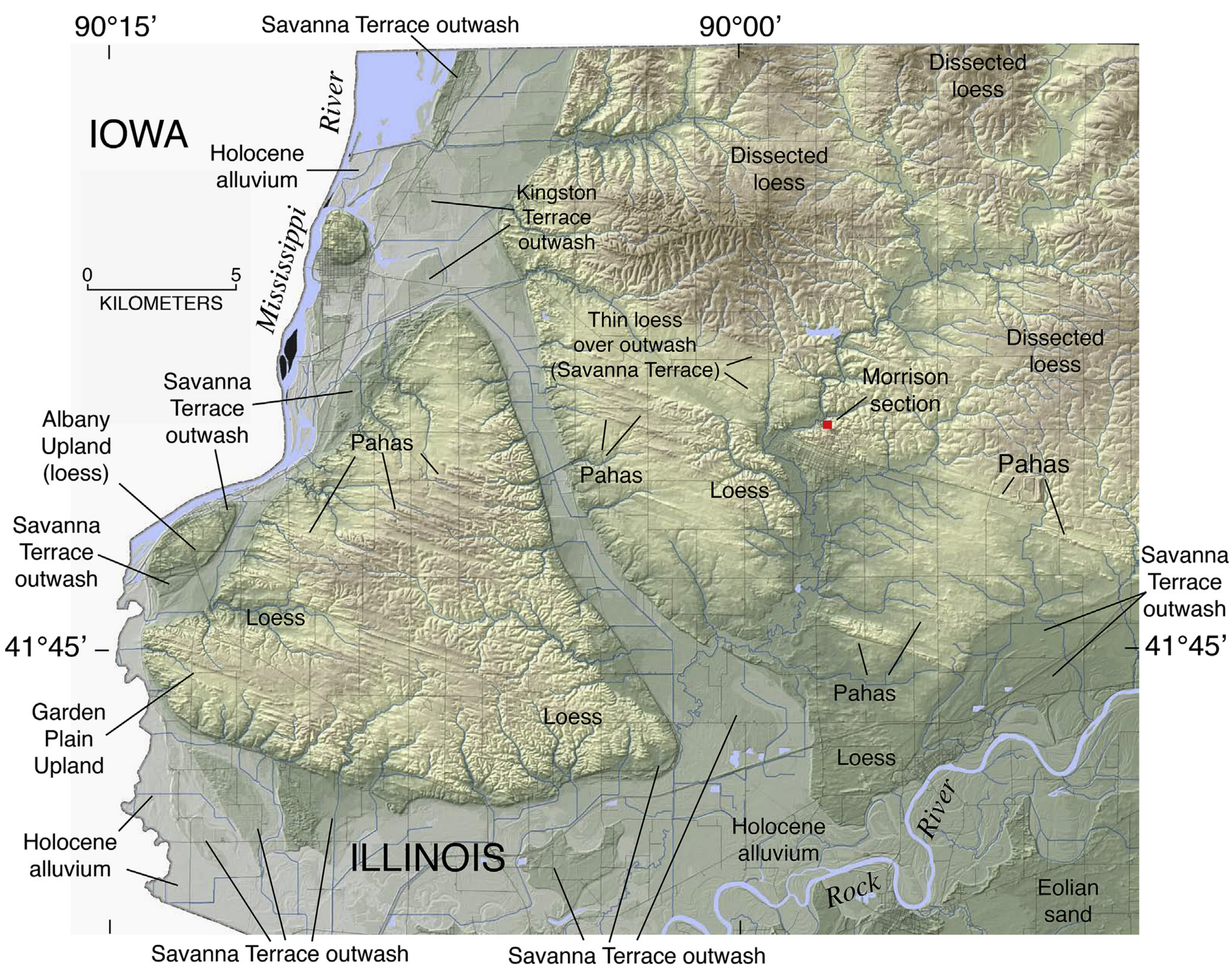

Fig. 11. Lidar image of a portion of Whiteside County, northwestern Illinois, showing the Mississippi River and floodplain, dissected Peoria Loess terrain, northwest-to-southeast-trending “paha” landforms (see discussion in text) in loess, areas of last-glacial outwash terraces, and location of the Morrison, Illinois loess section. Image courtesy of Dr. Donald E. Luman, Illinois State Geological Survey (retired); see also Domier and Luman (2014). Areas of late Pleistocene outwash are from Anderson and Miao (2013).

Frye et al. (1968) originally described the Quaternary sediments at Morrison from a carbonate bedrock quarry exposure. Although parts of the quarry wall exposure are still visible (Fig. 4b), colluvium and spoil have covered most of the section. Therefore, a core was taken on a nearby flat, stable, uncultivated upland a few tens of meters to the south of the quarry edge, adjacent to the local cemetery. As observed at Mount Vernon, Indiana, the section at Morrison provides an unusually complete record of late Quaternary loess accretion and soil formation (Fig. 12). Frye et al. (1968) reported a total Quaternary section thickness of ~15.5 m (with ~11.6 m of Peoria Loess). Our drill core yielded ~20 m of Quaternary section (with ~16.7 m of Peoria Loess). At the base of the section, the Sangamon Soil, developed in Loveland Silt in its upper part and till in its lower part, has fairly well expressed E and Bt horizons, with reddish yellow colors (7.5YR 6/6, dry) in the Bt horizon. The Farmdale Soil, ~1.7 m thick, with its brown (10YR 5/3, dry) A horizon, and pale brown (10YR 6/3) E horizon, has developed in Roxana Silt and overlies the Sangamon Soil. Above the Farmdale Soil is a mixing zone, ~0.6 m thick, that is transitional between this paleosol and the overlying loess, and may have formed by faunal mixing during the earliest stages of last-glacial loess accumulation.

The majority of the section (~16.7 m) is composed of massive, very pale brown (10YR 7/4, dry), silt-rich Peoria Loess of last-glacial age. In addition, we encountered a thin sand-rich layer within Peoria Loess at a depth of 11.4 m and a red, clay-rich bed at a depth of 10.8 m. The red clay bed resembles similar features in loess reported by McKay (1979b), Hajic et al. (1991), and Grimley et al. (1998) farther south in the Mississippi River valley of Illinois, although the features there are brown rather than red. There, the clay beds have been interpreted as representing peak glacial aggradational floods due to backwater flooding lower in the drainage system. A similar interpretation is made for the red clays observed here. The elevation of the red clays within the section and the elevation of the top of the Savanna Terrace to the northwest of Morrison (Fig. 11) are similar (slightly over ~200 m above sea level), which supports this interpretation.

The chronology for the accumulation of Peoria Loess at Morrison is based on five radiocarbon ages (Table 1). Humic acids extracted from the upper part of the Farmdale Soil at 18.0 m yielded a calibrated radiocarbon age of ~35.7 ka. Within Peoria Loess, at depths of 14.5 m, 13 m, 10.5 m and 3.35 m, we recovered snails of the Succineidae family. Radiocarbon analyses of the snails from these depths gave calibrated ages of ~23.8 ka, ~23.1 ka, ~21.5 ka and ~18.8 ka, respectively (Table 1). The upper ~1.7 m of Peoria Loess at Morrison contains an Alfisol with an A/E/Bt/BC/C profile, previously described by Muhs et al. (2001). This soil, with its well-developed, clay-rich Bt horizon (Fig. 12), indicates that there has been little erosion at the site since the final episode of loess deposition.

Bulk mineralogical analyses were conducted on samples from the entire section at Morrison. Bulk mineralogy is considered to be representative primarily of the silt fraction, which constitutes the majority of particles within loess (see discussion below). Within unweathered Peoria Loess but below the modern soil, quartz, plagioclase, K-feldspar, dolomite and calcite are present at all depths, and small amounts of amphibole are present in many samples. The Sangamon Soil, Farmdale Soil, and modern soil all show evidence of significant amounts of chemical weathering, as indicated by plagioclase depletion (low Na_2O/TiO_2), possibly some K-feldspar and/or mica depletion (low K_2O/TiO_2), and apatite depletion (low P_2O_5/TiO_2), relative to their loess parent materials (Fig. 12).

Within Peoria Loess at Morrison, the dominant particle size is

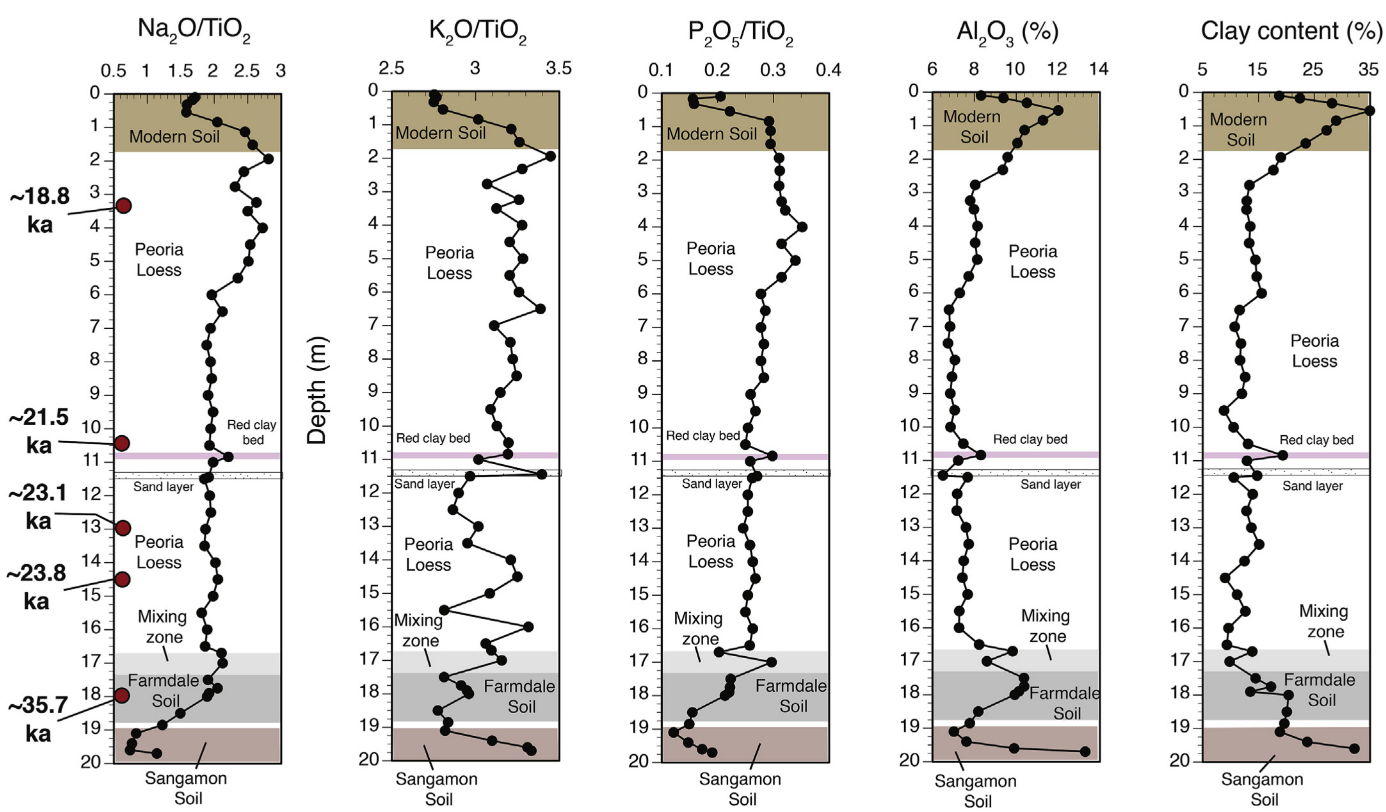

Fig. 12. Variations in Na_2O/TiO_2, K_2O/TiO_2, and P_2O_5/TiO_2 values as a function of depth in the Morrison loess section; note lower values of these measurements in modern soil and paleosols. Also shown is the abundance of the Al_2O_3 content as a function of depth, which shows parallel variation with clay (<2 μm) content. Calibrated radiocarbon ages from this site are in bold, black type and are from Pigati et al. (2015) and the present study (Table 1).

quite variable (Fig. 13). Sand (>53 μm) content is low in the oldest part, and generally increases up-section, reaching values as high as ~35% in the upper part. Coarse silt (53-20 μm) is quite variable as well, and ranges from ~35% to ~72%. This particle size fraction is generally highest in the middle part of the section. Fine silt (20-2 μm) shows little variation as a function of depth and ranges from ~10% to ~38%. Ratios of coarse-to-fine silt reach values greater than four at several points within the section. With three exceptions (at 1.9 m and 2.3 m, immediately below the modern soil, and within the "red clay" bed), clay (<2 μm) content in unweathered Peoria Loess (tracked closely by Al_2O_3 content) ranges from ~9% to ~15% (Fig. 12).

Laser particle size analyses provide additional details about the nature of the Peoria Loess at Morrison (Fig. 14). In the lowest part of the section, Peoria Loess (for three samples) has primary modes at ~30 μm, ~45 μm and ~50 μm, coarsening upwards. A very small secondary mode occurs in two of these samples within the sand-sized range. In the middle part of the section, there are modes at 40–50 μm, and in the upper part, there are modes at ~50 μm. All these measurements are consistent with conventional sieve/pipette measurements, indicating that the loess at Morrison is relatively coarse grained. In contrast, Iowa loess samples (localities IA-500, IA-700, and MC5, shown in Figs. 6 and 7) have primary modes at ~30 μm, considerably finer grained than most samples at Morrison.

In a review of loess transport mechanisms, Tsoar and Pye (1987) pointed out that sand is transported mainly by saltation, coarse silt mainly by short-term suspension, and fine silt by long-term suspension. Given the particle size distribution of Peoria Loess at Morrison, particles within the loess body could have been transported by all three mechanisms. With abundant coarse silt contents, short-term suspension appears to have been the dominant process throughout much of the period of Peoria Loess accumulation at Morrison, implying a source that was not far away. Nevertheless, contributions from long-term suspension transport for a significant amount of the sediment body is implied by the fine silt and clay contents.

Variability in the clay mineralogy at Morrison as a function of depth was the key property used by Frye et al. (1968) to define loess mineral zones. The two clay mineral species that define the mineral zones within Peoria Loess best, as shown by Frye et al. (1968), are what they termed "illite" and "expandable clay minerals." Moore and Reynolds (1997, p. 150–151) have pointed out ambiguities with the term "illite," which has been applied to a wide variety of K-rich,

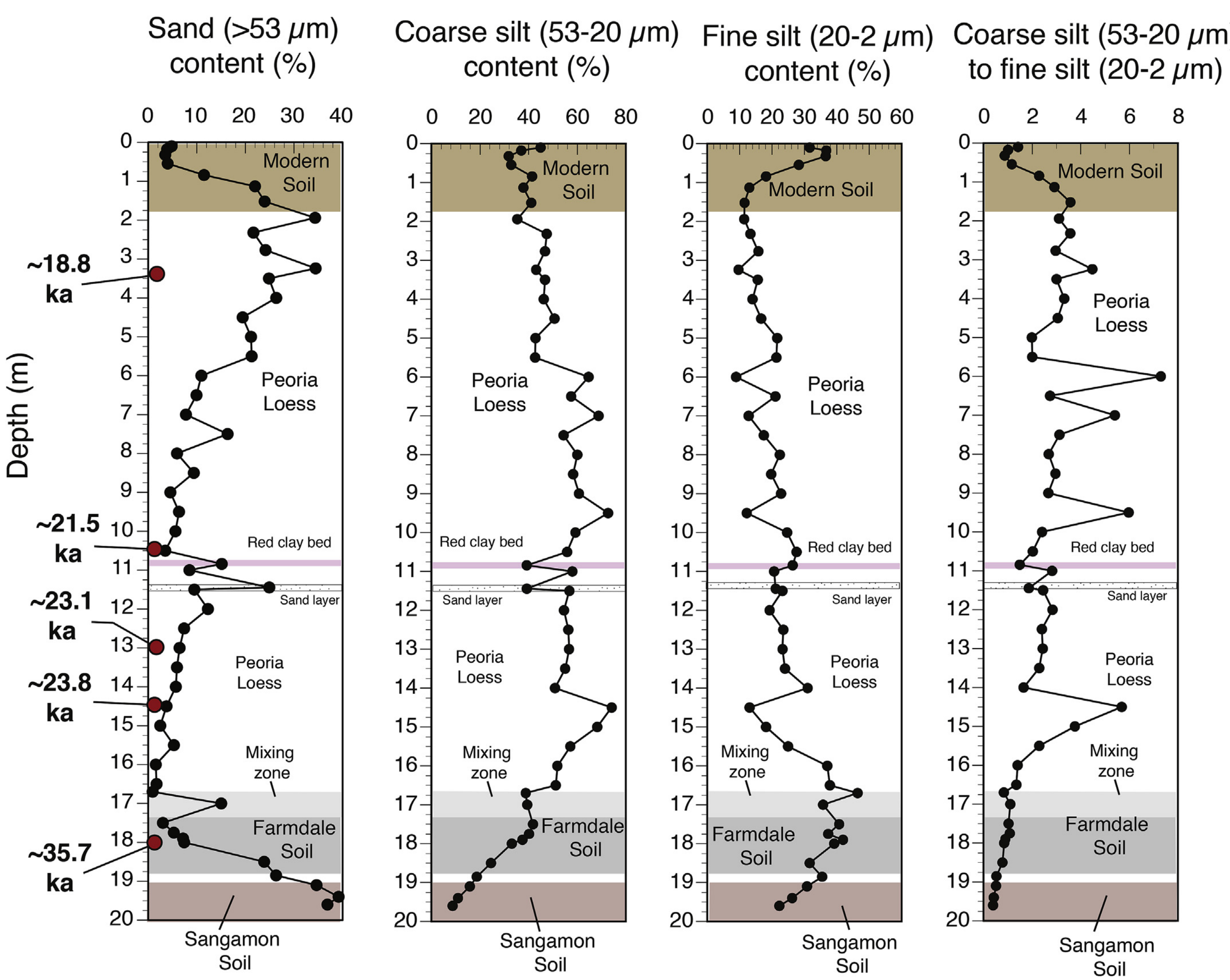

Fig. 13. Variations in loess particle size class shown as a function of depth in the Morrison loess section. Calibrated radiocarbon ages from this site are in bold, black type and are from Pigati et al. (2015) and the present study (Table 1).

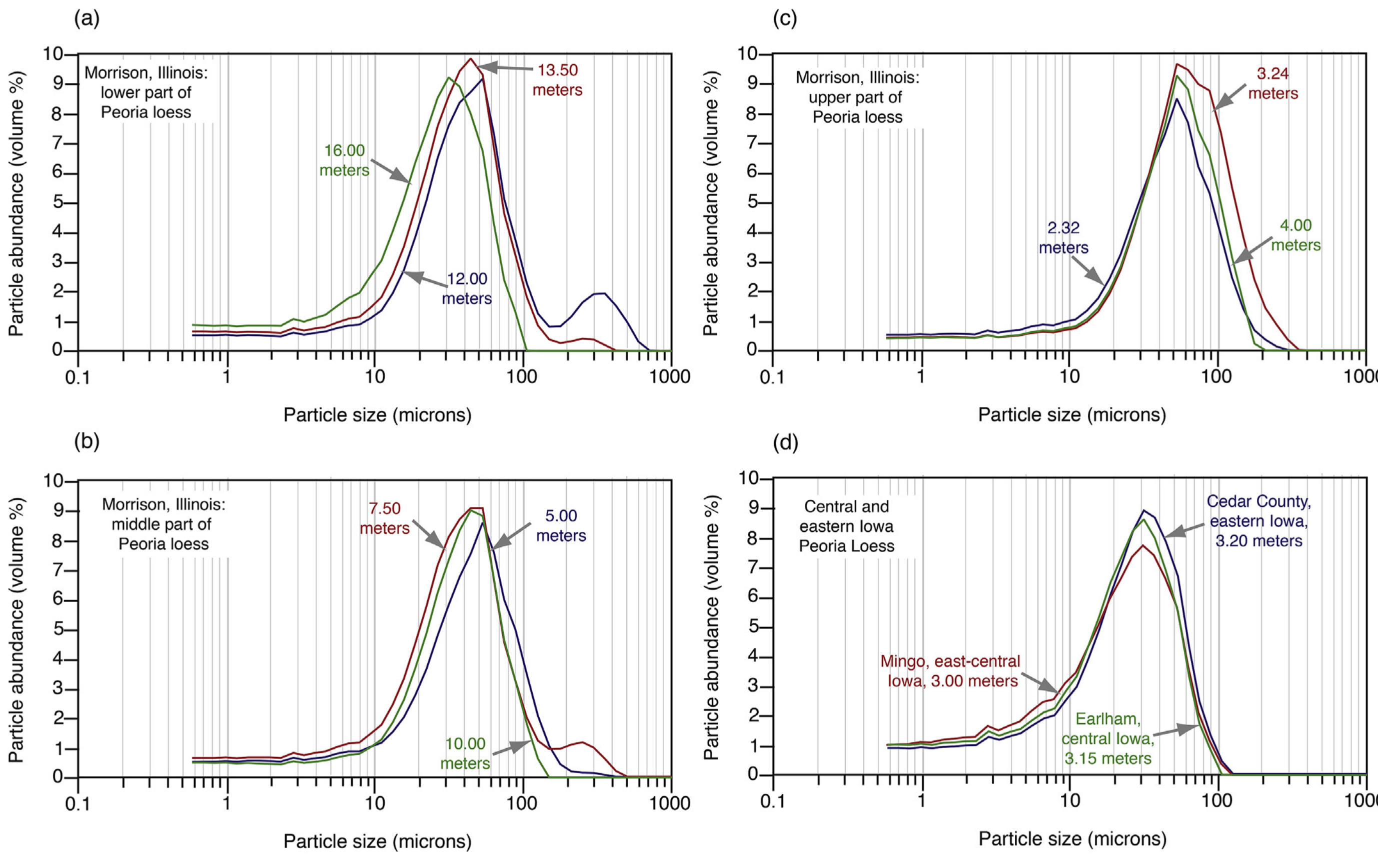

Fig. 14. (a), (b), (c) Histograms showing detailed particle size distributions at different depth intervals of Peoria Loess at Morrison, Illinois. (d) Similar data for Peoria Loess in eastern Iowa (localities shown in Figs. 6 and 7). All analyses were conducted using a laser particle size method.

phyllosilicate minerals. Thus, we prefer to use the more general term "mica," which includes what has traditionally been called "illite" in loess studies in Illinois. We also use the term "smectite" in preference to "expandable clay minerals." However, we note that the XRD peak positions that Frye et al. (1968) use to identify "illite" and "expandable clay minerals" are identical to what we use to identify "mica" and "smectite," respectively.

Mica is the dominant clay mineral found in Peoria Loess of southern Indiana (Fig. 15a) and smectite is the dominant clay mineral found in Peoria Loess of Iowa (Fig. 15b). Peoria Loess at Morrison contains intermediate quantities of these two clay minerals (Fig. 15c). When the abundance of mica at Morrison is plotted as a function of depth, it is apparent that the lower and upper parts of Peoria Loess have intermediate quantities, whereas the middle part has higher quantities (Fig. 16). Within Peoria Loess, quantities of smectite show a reciprocal relationship to mica abundances. In the quarry exposure they studied at Morrison, Frye et al. (1968) identified what they called Zone I (low illite), Zone II (intermediate illite), and Zone IV (low illite), going from the base of Peoria Loess to the top of this unit. The clay mineralogy of our core shows XRD patterns (Fig. 15) and calculated mica (illite) abundances (Fig. 16) that suggest a closer correspondence to Zone II (intermediate mica/illite), Zone III (high mica/illite), and Zone IV (low mica/illite), going from the base of Peoria Loess to the top of the section.

Frye et al. (1968) also reported variable amounts of dolomite and calcite in the section at Morrison, although their data are semi-quantitative. McKay (1977) studied loess sections over much of Illinois, including Morrison, and reported quantitative abundances of these two minerals. From our analyses, equivalent $CaCO_3$ (reflecting both dolomite and calcite), CaO + MgO + LOI (a geochemical proxy for dolomite and calcite combined), dolomite/quartz peak heights, and calcite/quartz peak heights all show depletions within the Sangamon Soil, Farmdale Soil, and modern soil (Fig. 16). Within Peoria Loess, carbonate minerals are present at almost all depths, but there is considerable variability in abundances. Of the two carbonate minerals at Morrison, McKay (1977) showed that dolomite contents exceed those of calcite by a factor of 4–21. Thus, 80–95% of what is apparent from the equivalent $CaCO_3$ content and CaO + MgO + LOI plots in Fig. 16 is likely from dolomite. Over most of the depth of Peoria Loess at Morrison, equivalent $CaCO_3$ content varies from ~15 to 28% (Fig. 16). This range agrees well with that of McKay (1977), who reported a dolomite-plus-calcite content range of 14–27% at Morrison.

Similar to clay minerals, carbonate minerals also show zonations within Peoria Loess at Morrison. Carbonate mineral content, as proxied by CaO + MgO + LOI, allows us to recognize three zones within Peoria Loess: from ~16.5 to 11.0 m, these values range from 21 to 28%; from 10.5 to 6.5 m, values range from 28 to 31%; and from 6.0 to 2.7 m, values range from 19 to 26%. Based on these measurements, as well as equivalent $CaCO_3$ values and XRD data, our interpretation is that these depth intervals correspond to McKay's (1977, 1979a) dolomite zones p-3 (intermediate dolomite content), p-5 (high dolomite content), and p-6 (low dolomite content), from bottom to top. McKay (1977) recognized the same dolomite zones at Morrison.

4.2.2. Rapids City, Illinois

The Rapids City, Illinois loess section is situated south of Morrison, but is also close to the Mississippi River in an area of thick loess (Fig. 3). At this locality, Frye et al. (1968) apparently sampled

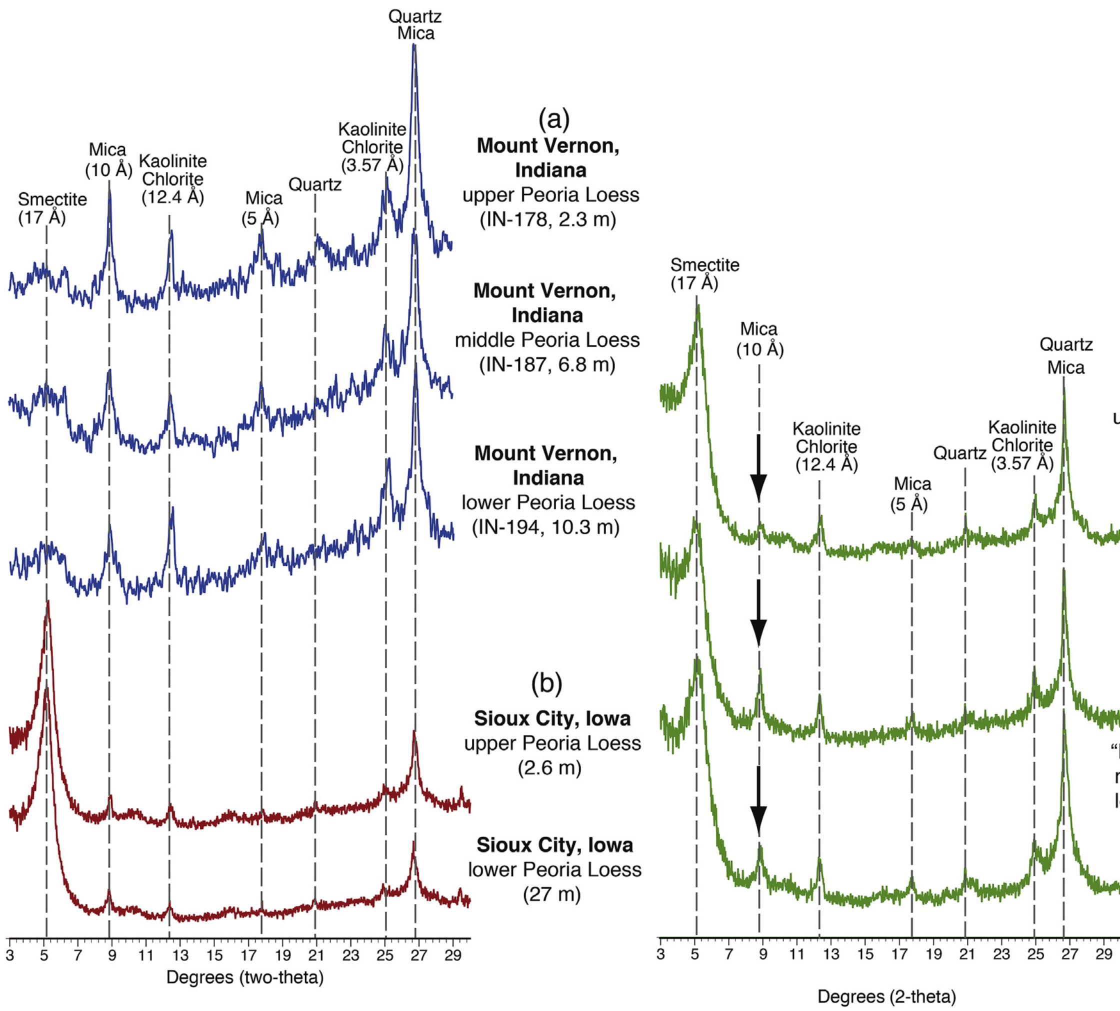

Fig. 15. Representative diffractograms of the clay (<2 μm) fraction of: (a) loess from Mount Vernon, Indiana, showing low smectite and high mica contents; (b) loess from Sioux City, Iowa (see Muhs et al., 2008a, 2013 for location), showing high smectite and low mica contents; and (c) Peoria Loess from the Morrison loess section at three depth intervals, showing the relative differences in heights of smectite and mica.

loess from at least two road cut exposures, but how the depths at one exposure correlate to depths at the other is not entirely clear from their report. Thus, the mineral zonation they present for this section is open to some question because of stratigraphic uncertainties. We re-sampled the section by drilling at a single site.

Rapids City, like Mount Vernon and Morrison, contains a nearly complete record of late Quaternary loess accumulation and soil formation (Figs. 17 and 18). The base of the core hosts the Sangamon Soil, developed in pebbly till that was thought by Frye et al. (1968) to be of Illinoian age (MIS 6). The Sangamon Soil here was apparently in a poorly drained position compared to Morrison, as it is characterized by a distinct, clay-rich, light gray (2.5Y 7/2, dry) Bg horizon; A and E horizons, likely present originally, are absent. The Sangamon Soil is overlain by the Farmdale Soil developed in Roxana Silt. The Farmdale Soil is just under a meter thick and is easily recognizable by its dark grayish brown (10YR 4/2, dry) A horizon. There is a thin (~20 cm) mixing zone above the Farmdale Soil that transitions into massive, very pale brown (10YR 7/4 to 10YR 7/3, dry), silt loam Peoria Loess at a depth of ~9 m. Peoria Loess at this depth continues upward to the modern soil at the top of the section. No significant changes in sedimentology occur up-section through Peoria Loess until the modern soil is encountered. This soil has an A/E/Bt/BC/C profile that is 1.63 m thick to the base of the Bt horizon (Muhs et al., 2001).

Eight radiocarbon ages, including four newly calibrated analyses from Muhs et al. (2001) and four new ages from the present study, provide a chronology for the Rapids City loess section (Table 1). Charcoal and humic acids from the lower Farmdale Soil give calibrated ages of ~32.2 ka and ~31.2 ka, respectively, concordant within the limits of analytical uncertainty. Wood and humic acids from the upper Farmdale Soil give calibrated ages of ~28.0 ka and ~27.6 ka, respectively, that are in good agreement with one another and provide a maximum-limiting age for Peoria Loess above this paleosol. Spruce (?) needles and wood fragments from the lowest part of Peoria Loess yield concordant ages of ~25.4 ka and ~25.0 ka, respectively. The uppermost two ages are both from snails of the Succineidae family. Snails from 6.5 m depth give a calibrated age of ~23.1 ka, and those from a depth of 5.0 m give a calibrated age of ~21.2 ka.

The bulk mineralogy of Peoria Loess at Rapids City is similar to that observed at Morrison. Quartz, K-feldspar and plagioclase are found in all depth intervals. The presence of plagioclase and K-feldspar is also apparent in the plots of Na_2O/TiO_2 and K_2O/TiO_2 (Fig. 17). Small amounts of an amphibole mineral, probably hornblende, are present in about two-thirds of the samples. Dolomite is abundant at all depths within Peoria Loess at Rapids City, except in

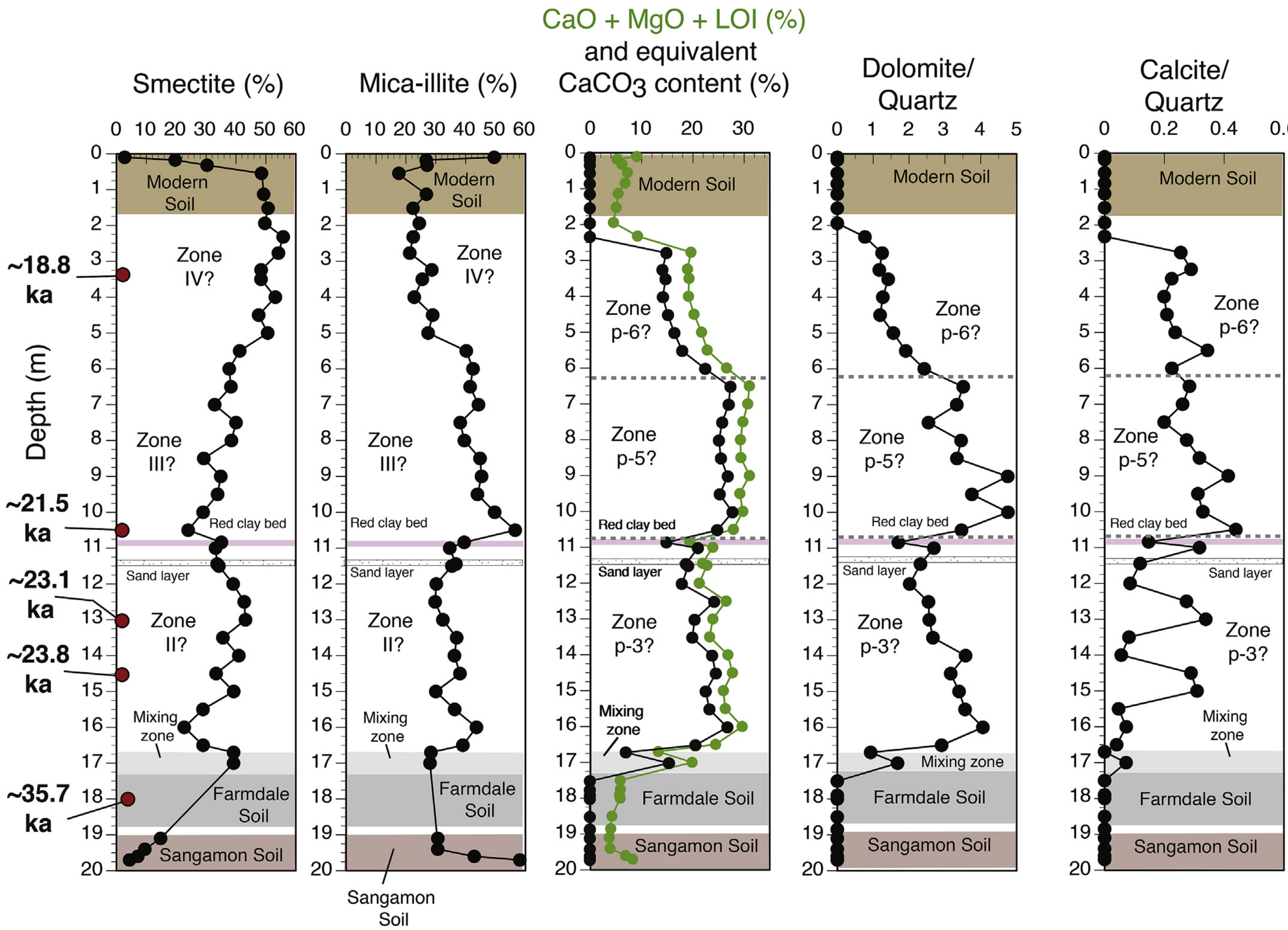

Fig. 16. Variations in smectite and mica content, geochemical measures of carbonate content (total $CaCO_3$-equivalent and CaO + MgO + LOI, in weight percent), and carbonate mineral content as a function of depth at the Morrison section. Dolomite/quartz and calcite/quartz values are taken from X-ray diffractogram (2-theta) peak heights for dolomite (30.9°), calcite (29.4°) and quartz (20.9°). Calibrated radiocarbon ages for this site are in bold, black type and are from Pigati et al. (2015) and the present study (Table 1). Possible correlation to clay mineral zones of Frye et al. (1968) are marked with Roman numerals and possible correlation to carbonate zones of McKay (1977, 1979a) are marked with "p" prefixes.

the modern soil (Fig. 18). The same is true for calcite, except that, as at Morrison, it is much less abundant than dolomite, and some of the lowest depth intervals of Peoria Loess have no detectable calcite.

As is the case with the Mount Vernon and Morrison sections, chemical properties in the section at Rapids City show significant changes as a function of depth due to pedogenesis (Figs. 17 and 18). The Sangamon Soil shows enrichment in Al_2O_3, due to pedogenic clay accumulation, but also displays evidence of plagioclase depletion (low Na_2O/TiO_2), K-feldspar and/or mica depletion (low K_2O/TiO_2), apatite depletion (low P_2O_5/TiO_2) and carbonate mineral depletion (low CaO + MgO + LOI). The Farmdale Soil shows far less dramatic evidence of chemical weathering than the Sangamon Soil. The modern soil shows some primary mineral depletion, intermediate between that of the Sangamon Soil and the Farmdale Soil.

Clay mineralogy at Rapids City is similar to that observed at Morrison. Mica abundances vary significantly as a function of depth (Fig. 18). Mica contents are high in two depth intervals, between ~9.0 and 8.2 m and between ~5.0 and 4.0 m, and significantly lower in other depth intervals. As at Morrison, smectite contents show a reciprocal relation to mica contents. We have not attempted to correlate these depth intervals with the clay mineral zones of Frye et al. (1968) at Rapids City.

In contrast, abundances of dolomite, calcite, and measures of equivalent $CaCO_3$ content and CaO + MgO + LOI allow recognition of four distinct zones (Fig. 18). From ~9.0 to 8.1 m, CaO + MgO + LOI values are 31–32%; from 8.0 to 5.5 m, values are 23–28%; and from 5.0 to 3.0 m, values are 26–30%. The fourth zone, above 3.0 m, has very low CaO + MgO + LOI values, but over much of this depth interval, the low carbonate contents are likely due to leaching during pedogenesis. The four carbonate zones appear to correlate, from bottom to top, with McKay's (1977, 1979a) dolomite zones p-2 (high dolomite), p-3 (intermediate dolomite), p-5 (high dolomite), and p-6 (low dolomite).

4.2.3. *Greenbay Hollow, Illinois*

Hajic et al. (1991), Grimley et al. (1998) and Muhs et al. (2001) have previously described the loess stratigraphy at Greenbay Hollow (Fig. 3). The Sangamon Soil is found at a depth of 10.3–11.8 m, and the Farmdale Soil occurs at 8.6–10.3 m depth (Fig. 19). At least three other paleosols, apparently developed in older loesses, were encountered between depths of 11.8 m and 18.5 m, and could be the equivalents of some of the pre-Sangamon Soil loesses described by Hajic (1986) from a nearby locality called Pancake Hollow, and by

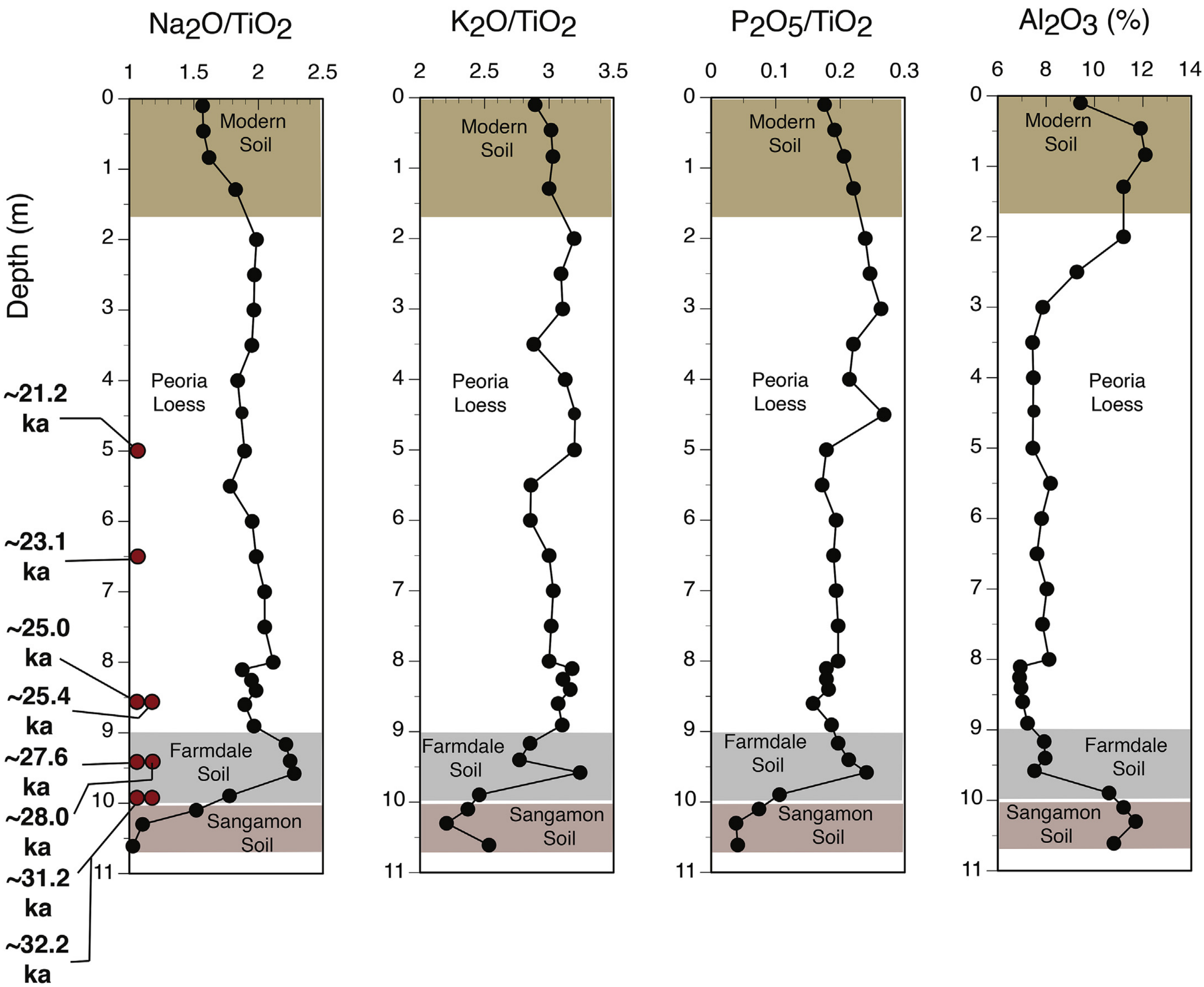

Fig. 17. Variations in geochemical properties as a function of depth in the loess section at Rapids City, Illinois, showing Na_2O/TiO_2, K_2O/TiO_2 and P_2O_5/TiO_2 values; note the lower values of these measurements in modern soils and paleosols. Also shown is the abundance of Al_2O_3 content as a function of depth, which is positively correlated with clay content. The calibrated radiocarbon ages from this site are in bold, black type and are from Muhs et al. (2001) and the present study (Table 1).

McKay (1979b) and Grimley et al. (2003) for other localities in southwestern Illinois. The older loesses are beyond the scope of the present study and are not discussed here.

Within Peoria Loess at Greenbay Hollow, two clay-rich beds were found, at depths of ~5.8 m and ~4.7 m (Fig. 19). Grimley et al. (1998) also reported two such beds and correlated them with similar, radiocarbon-dated clay beds from Bellefontaine Quarry, Missouri. At Bellefontaine Quarry, the clay beds are interpreted to be water-laid flood deposits. Thus, if the correlation of these beds between Greenbay Hollow and Bellefontaine Quarry is valid, then the loess just below the lower clay bed at Greenbay Hollow could be 19,660 ± 110 ^{14}C yr BP, the loess immediately below the upper clay bed at Greenbay Hollow could be 18,670 ± 170 ^{14}C yr BP, and the loess just above the upper clay bed could be 18,350 ± 110 ^{14}C yr BP. These radiocarbon determinations yield calibrated ages of ~23.5 ka, ~22.3 ka, and ~22.0 ka, respectively. Because these ages were not derived directly from Greenbay Hollow, they are queried in Figs. 19 and 20. We found no other dateable materials at Greenbay Hollow. The modern soil at the top of the section has an A/E/Bt/CB/C horizon sequence and is ~1.7 m thick to the base of the Bt horizon (Muhs et al., 2001).

Geochemistry and particle size data show evidence of significant changes in the physical and chemical properties of the modern soil and paleosols (Figs. 19 and 20). The Sangamon Soil shows a gradual down-core increase in clay content in the B horizon. This paleosol also shows evidence of loss of primary minerals by chemical weathering based on Na_2O/TiO_2 (plagioclase depletion), K_2O/TiO_2 (K-feldspar/mica depletion), P_2O_5/TiO_2 (apatite depletion), and CaO + MgO + LOI (carbonate mineral depletion). In contrast, the Farmdale Soil shows little evidence of clay accumulation or chemical weathering, except for loss of carbonate minerals. The modern soil at Greenbay Hollow exhibits evidence of carbonate loss, possible plagioclase loss and possible K-feldspar/mica depletion. Apatite depletion is evident below the A horizon of the modern soil based on the P_2O_5/TiO_2 values. There is a significant increase in clay content in the Bt horizon of the modern soil, mirrored by the abundance of Al_2O_3.

At another core site at Greenbay Hollow, Grimley et al. (1998)

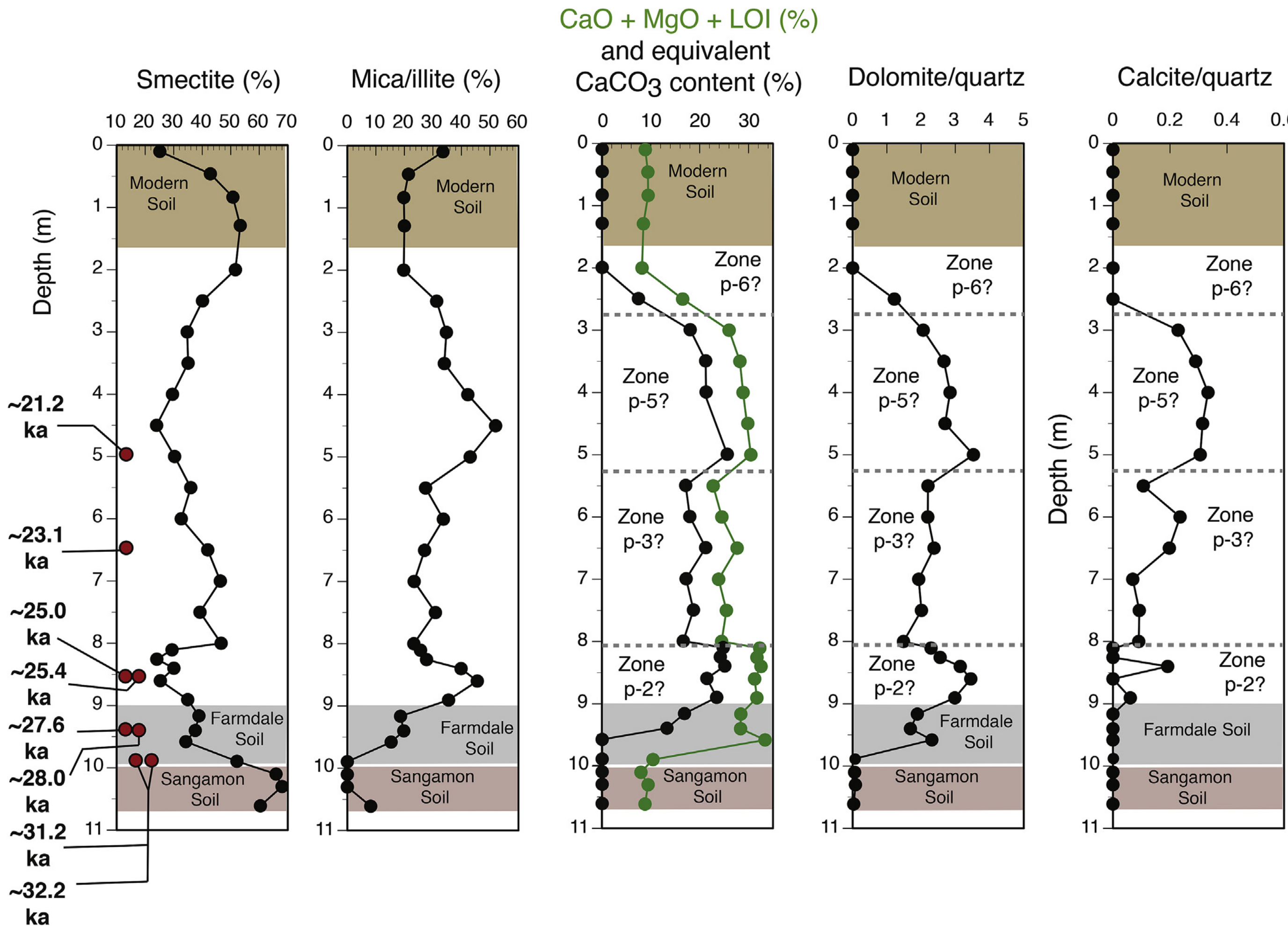

Fig. 18. Variations in smectite and mica content, geochemical measures of carbonate content (total $CaCO_3$-equivalent and CaO + MgO + LOI, in weight percent), and carbonate mineral content as a function of depth at the Rapids City section. Dolomite/quartz and calcite/quartz values are taken from X-ray diffractogram (2-theta) peak heights for dolomite (30.9°), calcite (29.4°) and quartz (20.9°). Calibrated radiocarbon ages for this site are in bold, black type and are from Muhs et al. (2001) and the present study (Table 1). Also shown is possible correlation of dolomite zones of McKay (1977, 1979a), indicated with a "p" prefix.

subdivided Peoria Loess into "lower," "middle," and "upper" zones, from oldest to youngest. Measurements of compositional variability within Peoria Loess at Greenbay Hollow presented here agree well with those of Grimley et al. (1998). To facilitate comparisons, we subdivided Peoria Loess in our core at approximately the same stratigraphic positions as Grimley et al. (1998), using the depths of the modern soil, the flood-related clay beds, the Farmdale Soil, and trends in low-field magnetic susceptibility as guides (Figs. 19 and 20). In the modern soil, there is clear evidence of plagioclase loss from Na_2O/TiO_2 values, as noted above. However, below this, Na_2O/TiO_2 is high in upper Peoria Loess, low in middle Peoria Loess, and reaches its highest values in lower Peoria Loess, consistent with plagioclase/quartz trends noted by Grimley et al. (1998). Measurements of coarse silt/fine silt, although determined with somewhat different particle size classes, also vary in a similar fashion to what Grimley et al. (1998) reported. This property is quite variable, but relatively high in the lower part of lower Peoria Loess, decreases upward to its lowest values in middle Peoria Loess, and is variable, but generally high again in upper Peoria Loess (Fig. 20). Low-field magnetic susceptibility is relatively high in lower and upper Peoria Loess compared to middle Peoria Loess, also in good agreement with Grimley et al. (1998). Total carbonate measurements within Peoria Loess (CaO + MgO + LOI) show low values in lower Peoria Loess, high values in middle Peoria Loess, and low values again in upper Peoria Loess, although some of the latter are due to carbonate mineral leaching during pedogenesis (Fig. 19).

4.3. Application of K/Rb and K/Ba as provenance indicators to upper Mississippi River valley loess of last glacial age

With the establishment of mineral zonation in Peoria Loess at Morrison using clay mineralogy and carbonate mineralogy, we investigated whether K/Rb and K/Ba values are distinctive for each zone. At Morrison, in Peoria Loess below the modern soil zone and above the Farmdale Soil, K/Ba and K/Rb values show rough parallels with carbonate mineral abundances, as proxied by CaO + MgO + LOI (Fig. 21). In the lowest depth interval (dolomite zone p-3 of McKay [1977, 1979a]), K/Ba ranges from 35 to 41 (with one anomalously high value of 45 at 13.0 m, marked by a query in Fig. 21); in zone p-5, the values range from 40 to 45; and in the upper zone p-6, values range from 33 to 39. For K/Rb, zone p-3 has values from 284 to 311 (with one anomalously high value of 332 at 13.0 m, marked by a query in Fig. 21); zone p-5 has values of 293–310; and zone p-6 has values 278–292. In summary, the highest K/Ba and K/Rb values are in zone p-5 and the lowest values

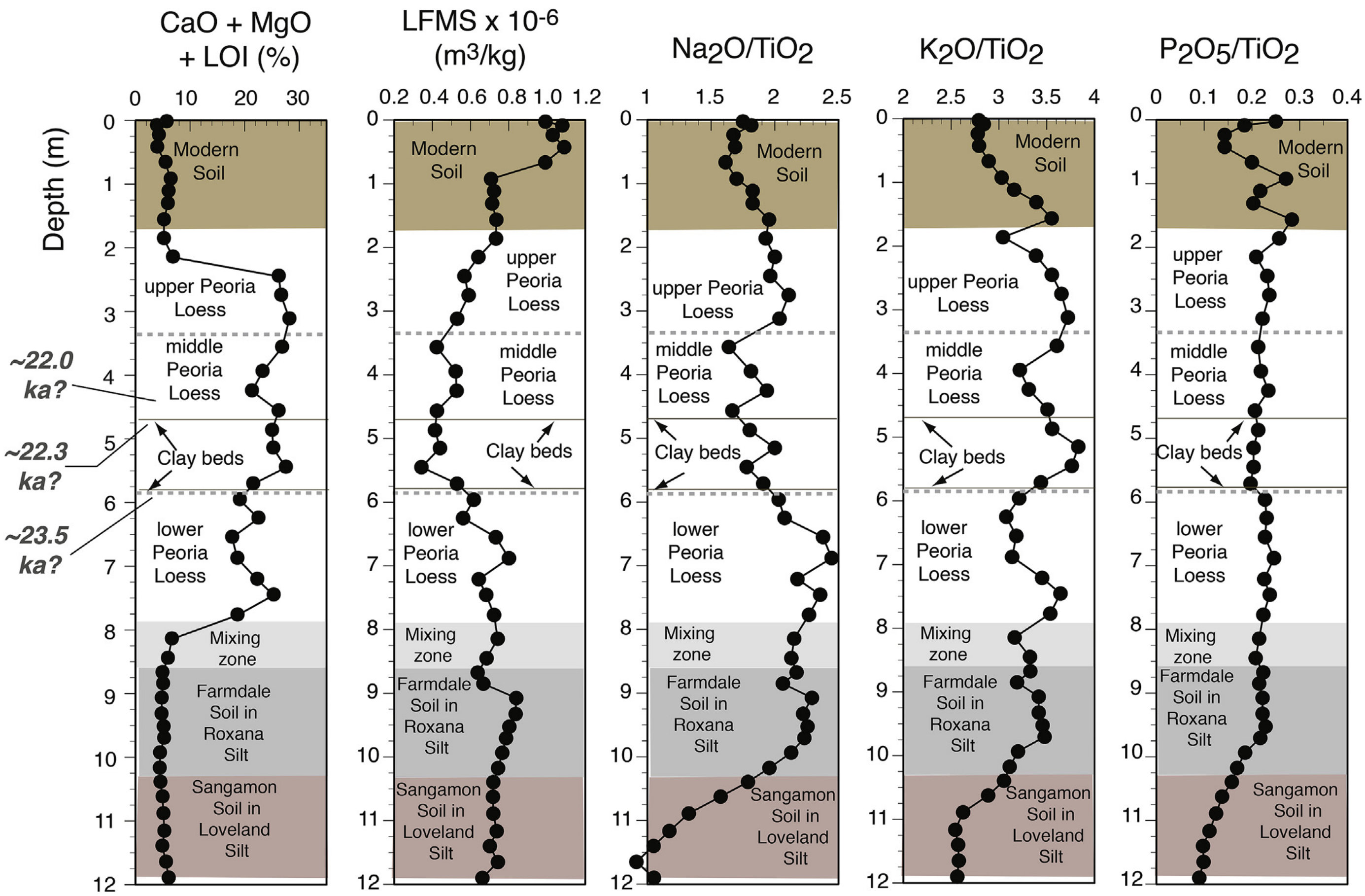

Fig. 19. Variations in geochemical properties as a function of depth in the loess section at Greenbay Hollow, Illinois showing CaO + MgO + LOI, low-field magnetic susceptibility (LFMS), Na_2O/TiO_2, K_2O/TiO_2, and P_2O_5/TiO_2values; note the lower values of the geochemical measurements in modern soils and paleosols. The designations of the mineralogical zones within Peoria Loess (lower, middle, and upper) are based on correlation to these boundaries from a nearby core studied by Grimley et al. (1998). Age estimates (calibrated radiocarbon ages) for the times of flood deposit events, marked by the clay beds, are in italics and queried, and are taken from Grimley et al. (1998).

are in zone p-6, with no overlap in ranges for these two zones. Zone p-3 has intermediate values. Thus, K/Ba and K/Rb values are consistent with the dolomite zones based on CaO + MgO + LOI at Morrison.

At Rapids City, there is also broad agreement between zones defined by carbonate mineral content and K/Ba and K/Rb values (Fig. 21). In the lowest depth interval of Peoria Loess, zone p-2, K/Ba has the highest range of values (43–45), zone p-3 above it has a range of 35–38, and zone p-5 has a range of 32–39 (Fig. 21). At the top, zone p-6 has the lowest range, 24–27, with one anomalous value of 32 at the contact between p-5 and p-6. Because most of the samples in the p-6 depth interval are from within the modern soil, we regard these values as tentative. Values of K/Rb at Rapids City also show some zonation, although they are less distinctive than for K/Ba. In zone p-2 at the base of Peoria Loess, K/Rb shows the highest range, 303–310; p-3 has a range from 271 to 298; and p-5 has a range from 267 to 287. As with K/Ba, the lowest K/Rb values are found within the modern soil that comprises much of zone p-6, with a range of 217–273.

At localities along the Illinois River, including Greenbay Hollow, Grimley et al. (1998) correlated their "lower-middle-upper" tripartite division of Peoria Loess with the dolomite zones of McKay (1977, 1979a). "Lower" Peoria Loess includes McKay's (1977, 1979a) dolomite zones p-1 (low dolomite), p-2 (high dolomite), and p-3 (intermediate dolomite); "middle" Peoria Loess corresponds to the lower part of p-5 (high dolomite); and "upper" Peoria Loess corresponds to the upper part of p-5. Our proxy for dolomite, CaO + MgO + LOI, shows similar variability in abundances over these three zones, as discussed earlier, and K/Ba shows a parallel tracking, where high carbonate zones tend also to be zones with higher K/Ba (Fig. 22). Higher values of K/Rb also tend to correspond to higher-carbonate zones, with the exception of the depth interval from ~6.5 m to ~7.0 m.

Thus, at all three localities studied here, K/Ba and K/Rb tend to track carbonate mineral (primarily dolomite) abundances at least to a first order of approximation. As pointed out earlier, loess sources in Iowa (glacial till and outwash from the Des Moines Lobe) have moderate amounts of carbonate minerals whereas loess sources in southern Indiana (glacial till and outwash from the Lake Michigan Lobe and other eastern lobes) have high amounts of carbonate minerals. It follows, therefore, that K/Ba and K/Rb in Illinois loess can be usefully compared to the ranges of these values in loess to the west (Iowa) and loess to the east (Indiana). Results show that at Morrison, K/Ba values in the p-3 zone fall between the ranges of Iowa and Indiana loess; values in the p-5 zone also fall between these two loess bodies, but are much closer to southern Indiana loess; and values in the p-6 zone again fall between the two loess bodies (Fig. 23). Values for K/Rb at Morrison follow those of K/Ba, except that in the p-3 zone, most points fall closer to the range for southern Indiana than is the case for K/Ba. At Rapids City, both K/Ba and K/Rb values in the p-2 zone fall within or close to the range for southern Indiana loess, zones p-3 and p-5 have intermediate

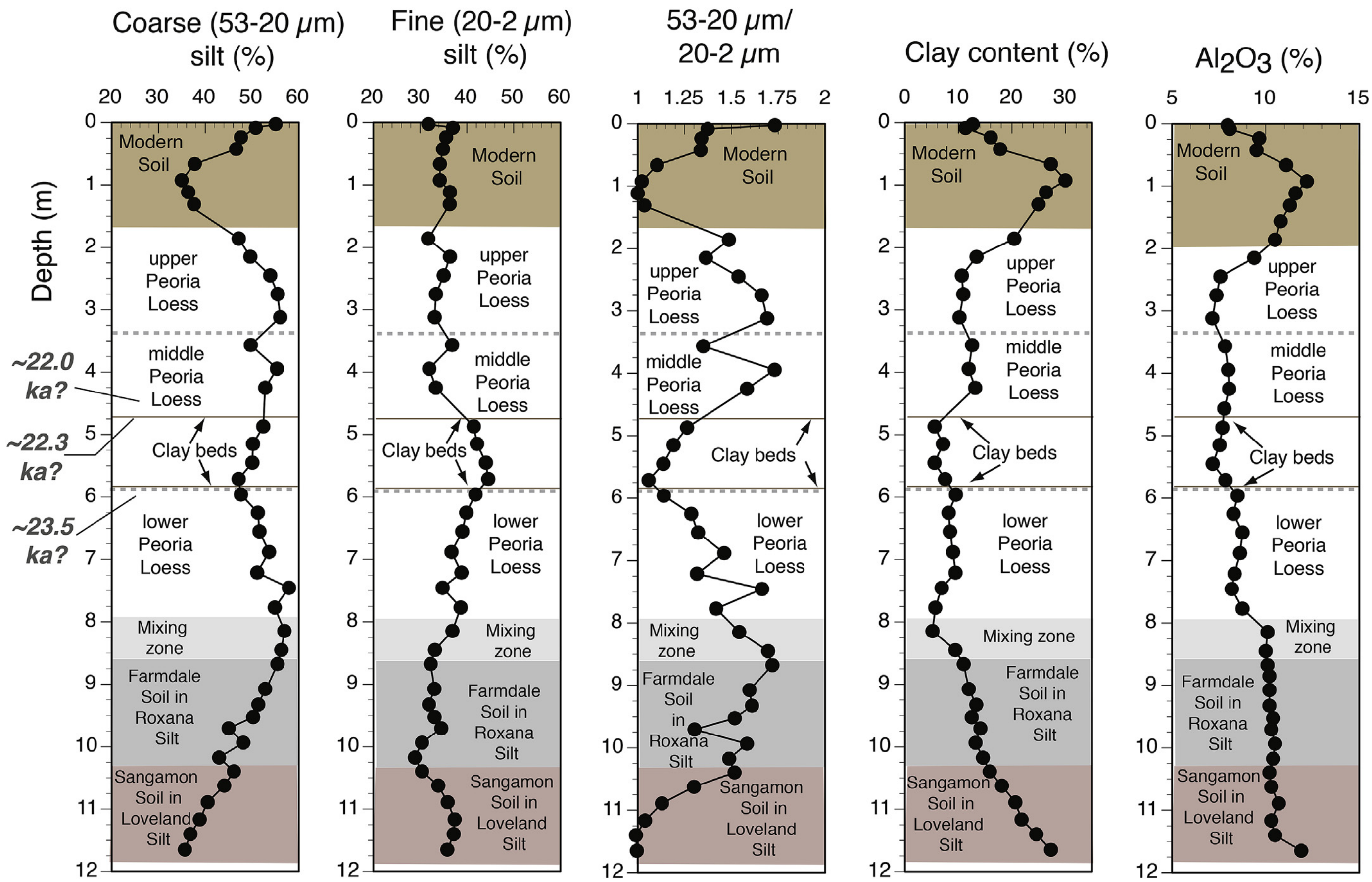

Fig. 20. Particle size variations as function of depth at Greenbay Hollow, Illinois. Also shown is the abundance of Al_2O_3 content, which parallels clay content. Age estimates (calibrated radiocarbon ages) for the times of flood deposit events, marked by the clay beds, are in italics and queried, and are taken from Grimley et al. (1998).

values, and zone p-6 values fall mostly within the range of Iowa loess (Fig. 23). At Greenbay Hollow, in both lower and middle Peoria Loess, there are some K/Ba and K/Rb values that fall within or close to the range for southern Indiana loess and other values that fall between Indiana and Iowa loess (Fig. 22). In upper Peoria Loess at Greenbay Hollow, there is a general decrease in K/Ba and K/Rb values upward, from points that fall close to the range for southern Indiana loess at lower depths to points that fall close to Iowa loess at shallower depths.

5. Discussion

5.1. Sources of loess related to dominant ice lobes and compositions of glacial tills

In the Mississippi River Basin, because loess is derived primarily from outwash that was eroded from glacial deposits, till composition is a first-order consideration in trying to identify loess provenance. Mudrey et al. (1982), Mickelson et al. (1983), Grimley (2000), Catacosinos et al. (2001) and Jirsa et al. (2011) show that there are diverse rock types over which lobes of the Laurentide Ice Sheet would have traveled in the upper Mississippi River Basin (Figs. 5 and 24). For example, the Des Moines Lobe and James Lobe of the Laurentide Ice Sheet eroded Precambrian igneous and metamorphic rocks, Cretaceous shale, and Paleozoic limestone and dolomite (Fig. 5). The Superior Lobe (and some of the smaller lobes around it: see Fig. 24) eroded terrains dominated by Precambrian igneous and metamorphic rocks, with smaller contributions from other rocks. The Green Bay and Lake Michigan lobes eroded terrains dominated by Paleozoic carbonates (mainly dolomites) and Paleozoic shales, with smaller amounts of Precambrian crystalline rocks. Given these lithologies, we can infer that in loess of the upper Mississippi River valley, quartz, plagioclase and K-feldspar are most likely derived from Precambrian igneous and metamorphic rocks; dolomite and calcite are derived from Paleozoic carbonate rocks; and clay minerals are derived from Paleozoic and Cretaceous shales.

Many studies have shown that clay mineralogy and carbonate mineralogy are particularly diagnostic of till compositions from different ice lobes. Des Moines Lobe and James Lobe tills are dominated by smectite in the clay fraction, with low amounts of mica, and the tills have moderate-to-high amounts of calcite and dolomite (Kemmis et al., 1981; Hallberg and Kemmis, 1986; Grimley, 2000). Superior Lobe and Rainy Lobe tills have intermediate amounts of mica compared to the lobes to the east and west, but contain little or no calcite and dolomite (Grimley, 2000). Tills of the Green Bay Lobe and Lake Michigan Lobe have high mica contents, low smectite contents, and high dolomite contents (Frye et al., 1969; Acomb et al., 1982; McCartney and Mickelson, 1982; Grimley, 2000; Jacobs et al., 2011). Hereafter, because of their mineralogical similarities, we refer to the Des Moines Lobe and James Lobe as "western lobes," the Superior, Rainy, and Chippewa lobes as "northern lobes," and the Green Bay and Lake Michigan lobes as "eastern lobes" (Fig. 24).

5.2. Drainage history and its effect on loess provenance

In addition to till composition, an important part of the entire loess generation cycle in the upper Mississippi River valley is the

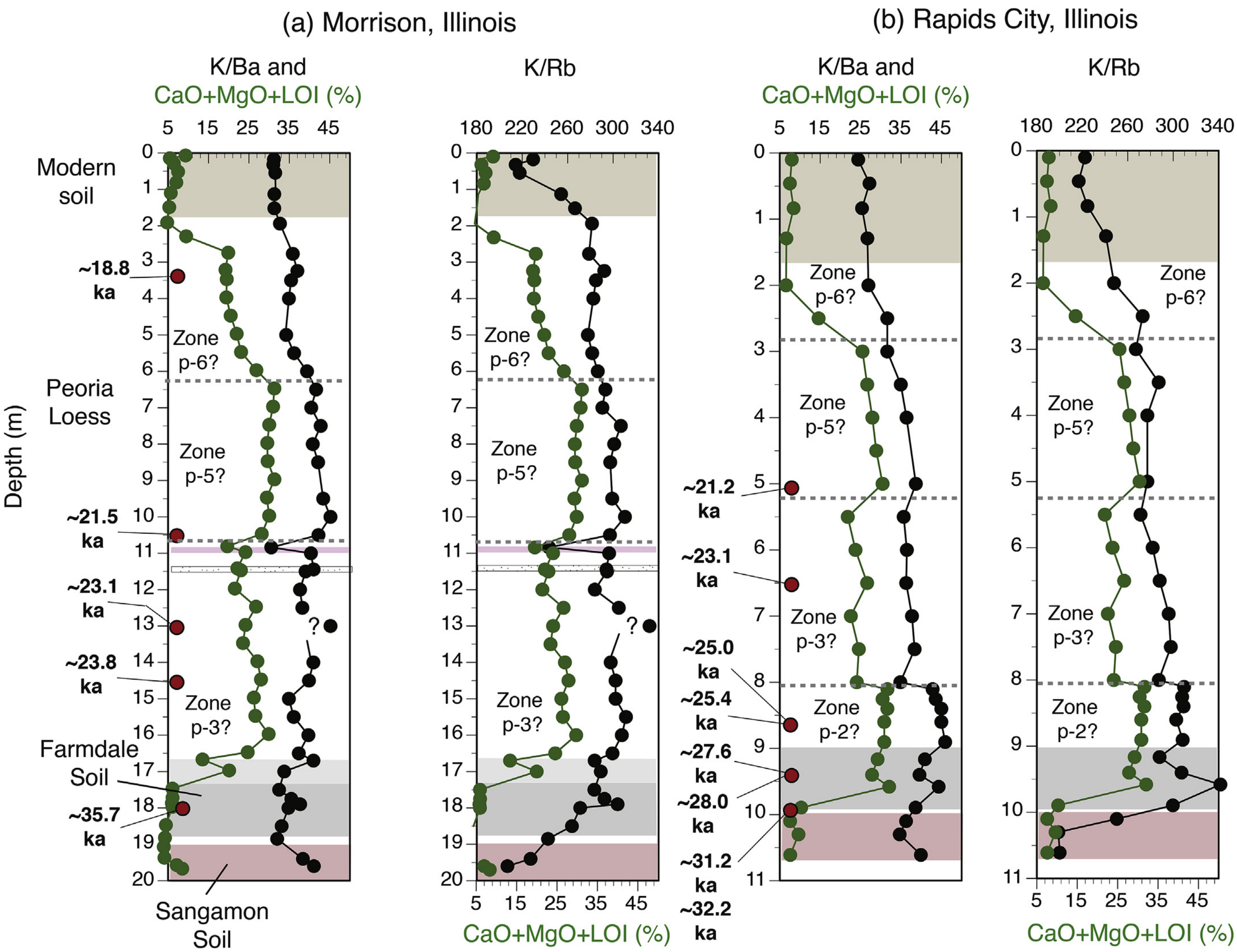

Fig. 21. Variations in K/Rb and K/Ba values as a function of depth in the loess sections at (a) Morrison and (b) Rapids City compared to total carbonate mineral content (proxied by CaO + MgO + LOI, shown in green). The anomalously high K/Ba and K/Rb values at 13.0 m at Morrison are shown with a query to the left of the data points. Also shown is possible correlation of dolomite zones of McKay (1977, 1979a), indicated with a "p" prefix. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

region's drainage history and its relation to ice lobe advances. North of the Rock River, where Morrison and Rapids City are situated, western lobe sediment could have been transported to the upper Mississippi River primarily via the Minnesota River and its tributaries, plus smaller drainages such as the Root River (Fig. 24). Northern lobes provided sediment to the upper Mississippi River Basin via the St. Croix, Red Cedar and Chippewa Rivers. The main carrier of sediment from an eastern lobe source (the Green Bay Lobe) to the upper Mississippi River would have been the Wisconsin River.

Farther south, in the region of Greenbay Hollow, the pathways of sediment delivery to the Mississippi River and Illinois River from various ice lobes become more complex. In addition to those described above, much more sediment from western lobes reached the Mississippi River via the Cedar, Iowa, Skunk and Des Moines Rivers in eastern Iowa (Fig. 24). Further, Green Bay Lobe sediment could have been delivered to the Mississippi River via the Rock River and its tributaries in southern Wisconsin and northern Illinois (Anderson, 2005).

A complicating factor to consider is any change in drainage systems brought about by advances and retreats of the ice lobes themselves. The three localities we studied were affected differently by changes in drainage during the last glacial period. The most important of these was the diversion of the Ancient Mississippi River (terminology from Frye et al., 1968) at the time of the maximum advance of the Lake Michigan Lobe (Shaffer, 1954; Glass et al., 1964; Frye et al., 1968; McKay, 1979a, 1979b; Curry, 1998). Prior to the advance of this ice lobe, the Ancient Mississippi River flowed in its present valley north of Rapids City, but just before reaching the Rapids City area, it turned southeastward and flowed into what is now the Illinois River valley (Figs. 3 and 25). From there, it flowed southward through the present Illinois River valley to where the modern confluence of the two rivers is situated (Fig. 25). At the time of the maximum advance of the Lake Michigan Lobe, ~24.4 ka (in cal yr; Curry, 1998; Curry et al., 2018), the ice diverted the river to where its present course is situated. This important event explains the depletion of western glacial lobe-derived sediment in middle and upper Peoria Loess along the Illinois River valley and its replacement by Lake Michigan Lobe-derived sediment (Frye et al., 1968; McKay, 1977, 1979a; 1979b; Grimley et al., 1998; Grimley, 2000).

Understanding how this diversion affected loess delivery along

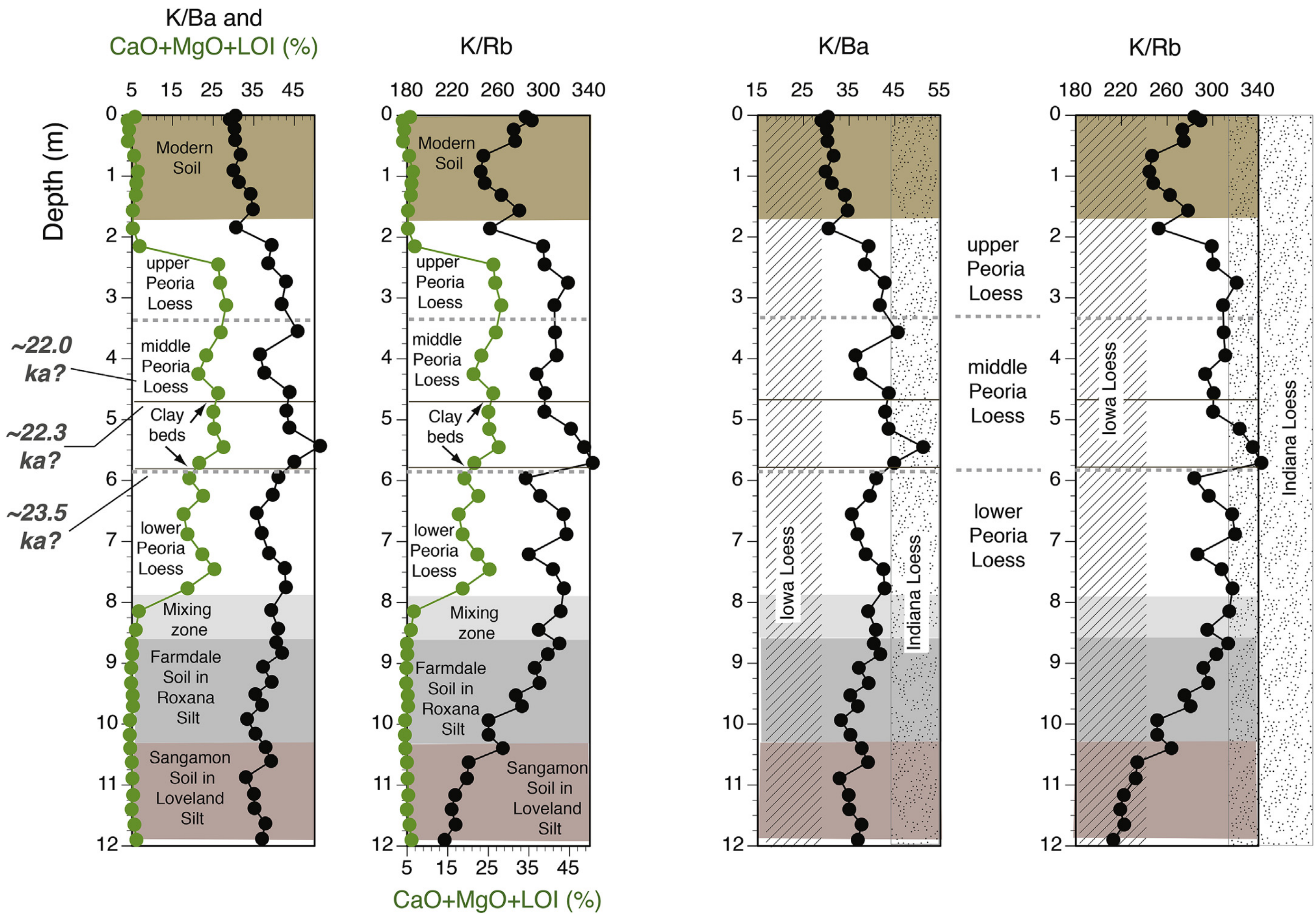

Fig. 22. Left two panels: variations in K/Ba and K/Rb values as a function of depth in the loess section at Greenbay Hollow compared to total carbonate mineral content (proxied by CaO + MgO + LOI, shown in green). Also shown is possible correlation of mineralogical zones in Peoria Loess (low, middle, high) to those of Grimley et al. (1998). Right two panels: K/Ba and K/Rb as a function of depth in the loess section at Greenbay Hollow compared to ranges of these values in Peoria Loess of central/eastern Iowa and southern Indiana (ranges taken from Fig. 9). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the Mississippi River is more complicated and depends on where one is looking along different reaches of the river. At Morrison, a locality situated upstream of the diversion (Fig. 25), there may have been little effect from this event, as the Ancient Mississippi River north of the site was situated geographically as it is now, and would have been the supplier of sediment with westerly or northwesterly paleowinds throughout the course of Peoria Loess deposition. Rapids City, situated immediately to the south of the diversion point (Fig. 25), would have received Mississippi River valley-derived sediment from westerly or northwesterly winds only *after* the diversion at ~24.4 ka. Prior to the diversion, Rapids City would not have been immediately downwind (i.e., east or southeast) of a major outwash-bearing drainage. The radiocarbon chronology supports this interpretation, as all but the lowermost part of Peoria Loess in the section at Rapids City is younger than the age of the diversion at ~24.4 ka (Figs. 17, 18 and 21).

Greenbay Hollow, much farther south, is situated between the present Mississippi and Illinois River valleys (Figs. 3, 24 and 25). Thus, prior to the diversion, Greenbay Hollow would have been west of the Ancient Mississippi River, but after the diversion it would have been east of it. A further complication for Greenbay Hollow is that prior to the diversion, the present Mississippi River valley between where the modern Iowa River flows into it and the Greenbay Hollow area was occupied by what Frye et al. (1962, 1968) and Glass et al. (1964) refer to as the "Ancient Iowa River" (Fig. 25). The Ancient Iowa River would have supplied sediment only from the western lobes.

Yet another factor to consider in understanding loess sources is the development of proglacial lakes. Proglacial lakes were extensive in North America during the last glacial period (Teller and Kehew, 1994), and their formation took place at different times, depending on the location of various lobes of the Laurentide Ice Sheet. It has long been recognized that proglacial lakes were effective "silt traps" that would have starved outwash-bearing rivers of particles that otherwise might have contributed to loess (Flint, 1971, p. 260). As an example, one of the most important of these proglacial lakes that could have affected the upper Mississippi River valley is glacial Lake Wisconsin, which formed adjacent to the Green Bay Lobe of the Laurentide Ice Sheet (Clayton and Attig, 1989). Prior to its catastrophic drainage, this lake would have trapped abundant silt from melt waters of the Green Bay Lobe that otherwise would have entered the Wisconsin River valley, an important tributary to the upper Mississippi River. Given this complex glacial, fluvial, and lacustrine history, along with the geochemical and mineralogical data presented earlier, we now attempt to integrate the factors of ice lobe advance and drainage history into an interpretation of how loess sources may have changed over the course of the last glacial period along the Mississippi River at each of our three study localities.

5.3. Morrison, Illinois

The loess section at Morrison is situated upstream (north) of where the Ancient Mississippi River was diverted by the advance of the Lake Michigan Lobe of the Laurentide Ice Sheet (Figs. 3 and 25). The mineral zones and geochemistry of this section nevertheless document a complex history of diverse sediment delivery to the upper Mississippi River Basin, most of it likely occurring after the last-glacial diversion. As discussed earlier, the lowest depth interval of Peoria Loess, immediately above the mixing zone above the Farmdale Soil, is correlated with McKay's (1977, 1979a) p-3 zone (intermediate dolomite contents; Fig. 16). The clay mineralogy also shows intermediate abundances of both smectite and mica (illite). K/Ba and K/Rb both show values that fall between the ranges of Iowa loess and Indiana loess (Fig. 23). We infer from these multiple lines of evidence that there were contributions from both western-source ice lobes and eastern-source ice lobes during the accumulation of loess at Morrison at this time. This earliest Peoria Loess accumulation took place after ~35.7 ka, based on the age from the Farmdale Soil, but this is a very broad maximum-limiting age and we suspect that loess accumulation did not begin until many thousands of years later. Within the p-3 zone, but higher in the section, loess accumulation was still ongoing as late as ~23 ka and ended sometime before ~21.5 ka (Fig. 16). During this time interval, the Green Bay Lobe (an eastern source) had already advanced to its maximum southernmost position in southern Wisconsin (Fig. 26a) and outwash from this ice would have been delivered to the upper Mississippi River via the Wisconsin River (Fig. 24). Nevertheless, the clay and carbonate mineralogy, along with K/Ba and K/Rb values, imply that a western-source lobe of ice was also supplying sediment to the upper Mississippi River basin, north of Morrison. Part of this source could have been from till of the Lehigh Advance of the proto-Des Moines Lobe (Sheldon Creek Formation), which was apparently still in Iowa as late as ~29 ka (Fig. 26b). Later during this period of loess accumulation, the Des Moines Lobe was well north of the Iowa/Minnesota border (Figs. 24 and 26b), but it is possible that ice was still present in Minnesota. If so, this is the most probable source of the smectite and K-bearing minerals with lower K/Ba and K/Rb. Sediment from ice in Minnesota could have been delivered to the Minnesota River, a tributary to the upper Mississippi River (Fig. 24). Another possibility to explain the lower amounts of dolomite and intermediate amounts of mica (illite) would be partial derivation from northern-source glacial lobes, such as the Rainy or Superior lobes (Grimley, 2000), which are also drained by the upper Mississippi River (Fig. 24). Regrettably, K/Ba and K/Rb do not help determine whether northern lobes were contributors, because K/Ba in till of the Rainy and Superior lobes ranges from 26 to 51 and K/Rb ranges from 208 to 342 (Fig. 9). These values span the highest values of Iowa loess to the lowest values of Indiana loess (Figs. 9 and 23). We conclude, therefore, that the p-3

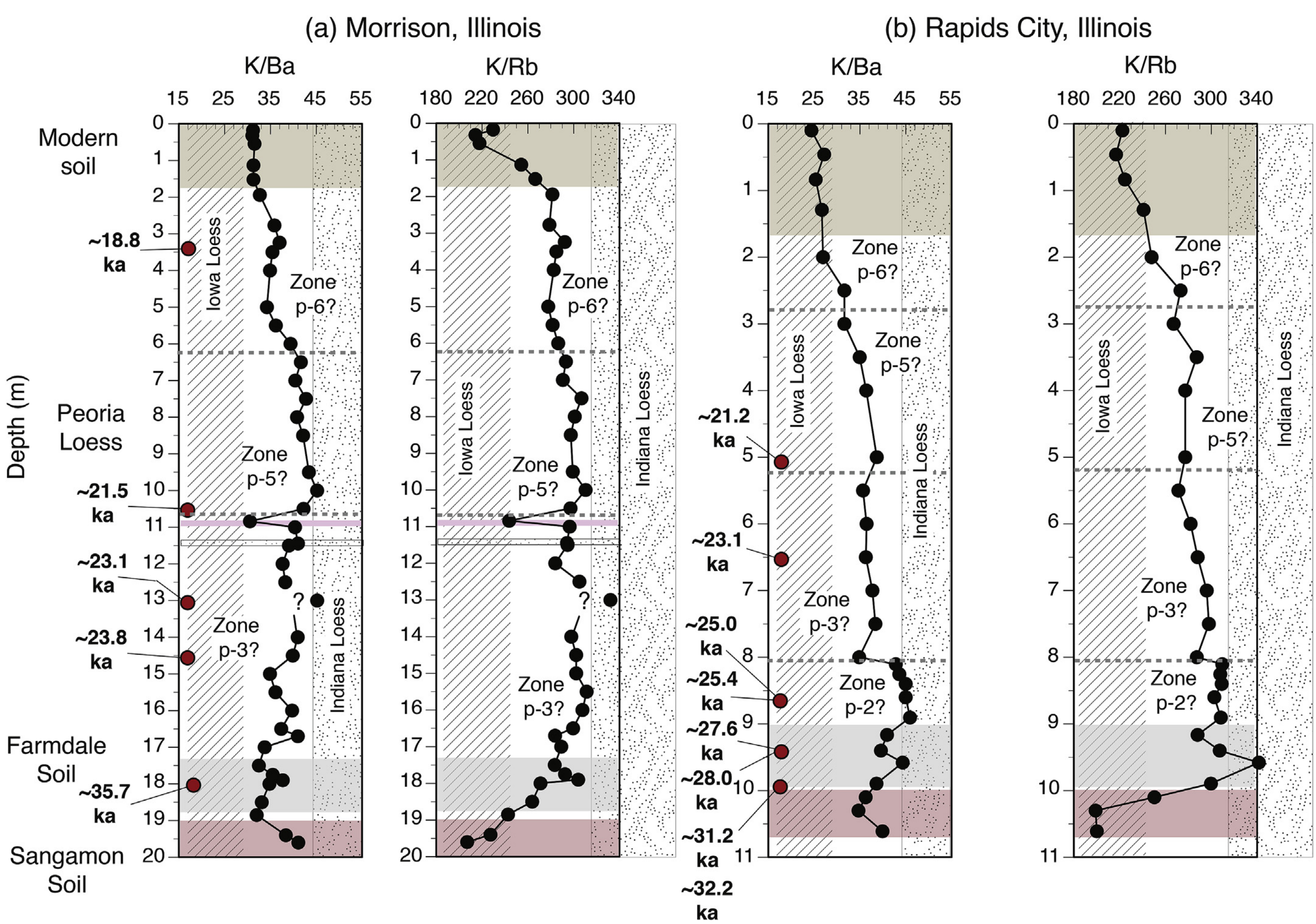

Fig. 23. K/Ba and K/Rb as a function of depth in the loess sections at (a) Morrison and (b) Rapids City compared to ranges of these values in Peoria Loess of central/eastern Iowa and southern Indiana (ranges taken from Fig. 9). The anomalously high K/Ba and K/Rb values at 13.0 m at Morrison are shown with a query to the left of the data points. Also shown is possible correlation of dolomite zones of McKay (1977, 1979a), indicated with a "p" prefix.

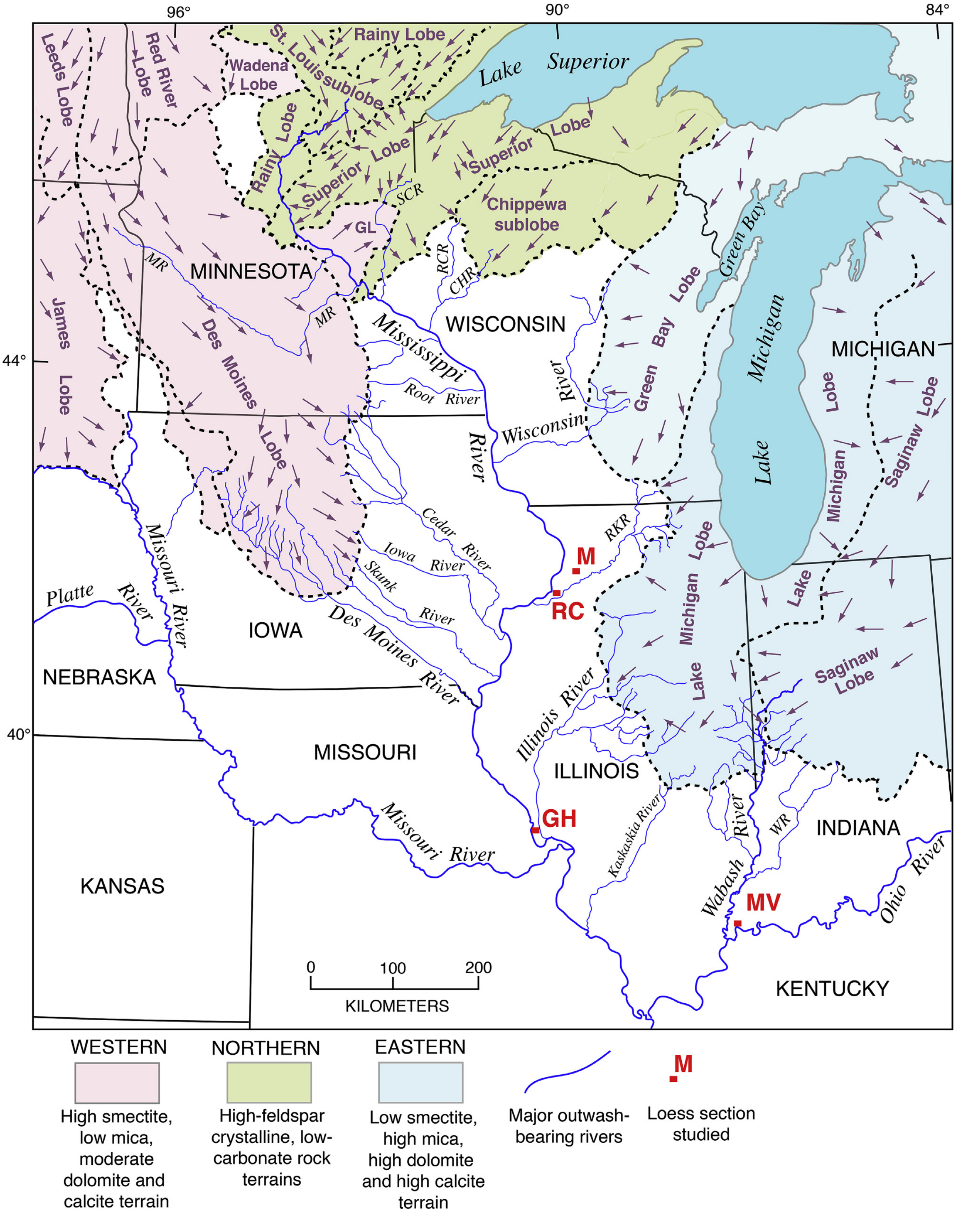

Fig. 24. Principal ice lobes in the southern Laurentide Ice Sheet during the last glacial period that supplied sediment to the Mississippi River. Also shown are inferred ice flow directions (arrows), the Mississippi River and major outwash-bearing tributaries to it (blue lines), and loess localities studied. GL, Grantsburg Lobe. Loess sections: M, Morrison; RC, Rapids City; GH, Greenbay Hollow; MV, Mount Vernon. Abbreviations for tributaries: SCR, St. Croix River; CHR, Chippewa River; MR, Minnesota River; RCR, Red Cedar River; RKR, Rock River; WR, White River. Different shades of ice lobes indicate differing bedrock lithologies over which the Laurentide Ice Sheet traversed (simplified from Mickelson et al., 1983). Western lobes in pink: Cretaceous and Paleozoic shales, moderate amounts of Paleozoic limestones and dolomites, and Precambrian igneous and metamorphic rocks. Northern lobes in green: mostly Precambrian igneous and metamorphic rocks. Eastern lobes in blue: Paleozoic limestones, dolomites, and shales, and Precambrian igneous and metamorphic rocks. The legend shows a typical till mineralogy derived from these different rock types (see text for discussion). Glacial lobes and flow directions are from Goebel et al. (1983), Lineback et al. (1983), Farrand et al. (1984), Gray et al. (1991), Hallberg et al. (1991) and Fullerton et al. (1995). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

zone at Morrison must have some component of a Green Bay Lobe source combined with a western source, a northern source, or both.

The middle depth interval of Peoria Loess at Morrison is correlated with McKay's (1977, 1979a) p-5 zone on the basis of the high carbonate content (Figs. 16 and 21). This zone also has the highest mica (illite) content within the entire section. Both of these characteristics imply major contributions to this loess zone by an eastern lobe source, which for the Morrison area would most likely be the Green Bay Lobe (Fig. 24). A Green Bay Lobe source of loess for the p-5 zone at Morrison is supported by K/Ba and K/Rb measurements, which reach their highest values within the section (Fig. 23). The base of this zone has a radiocarbon age of ~21.5 ka and the top of the zone is older than ~18.8 ka. This time period corresponds to the Johnstown Phase, a maximum extent southward of the Green Bay lobe in Wisconsin (Fig. 26). This was also the period when glacial Lake Wisconsin (Clayton and Attig, 1989) was in existence and the most recent estimates indicate that it was present from ~24 ka to ~19.5 ka; by ~19 ka, the lake had drained (Mickelson and Attig, 2017). It could be argued that because of this extensive sediment trap, little or no silt-rich outwash would have entered the Wisconsin River valley, the major tributary that could have supplied sediment to the upper Mississippi River valley from the Green Bay Lobe at this time. However, detailed geologic mapping of Sauk County, Wisconsin, where the southern margin of glacial Lake Wisconsin was situated, shows that there were still outlets to the Wisconsin River valley from the Green Bay Lobe, south of the Baraboo Hills (Attig and Clayton, 1990; Clayton and Attig, 1990). Thus, during the period from ~21.5 ka to sometime before ~18.8 ka, outwash from the Green Bay Lobe could still have supplied silt to the Wisconsin River valley, and that silt was then transported by this tributary to the Mississippi River, north of Morrison. In contrast, the main western source, the Des Moines Lobe, was well north of the Iowa/Minnesota border at this time and apparently supplied lesser amounts of sediment to the upper Mississippi River valley from tributaries in Minnesota (Figs. 24 and 26).

The uppermost loess at Morrison is correlated with McKay's (1977, 1979a) p-6 zone, characterized by relatively low carbonate mineral content and significantly lower mica (illite) content but higher smectite content (Figs. 16 and 21). The age of the base of this zone is unknown, but it is younger than ~21.5 ka and older than ~18.8 ka, based on the radiocarbon ages (Fig. 16). This zone also has a clear correlation with Frye et al.'s (1968) clay mineral zone IV. Frye et al. (1968) and Wascher et al. (1971) reported calibrated radiocarbon ages of ~19.3 ka from near the base of the zone and ~16.8 ka from near the middle of the zone from two other localities in northwestern Illinois, in broad agreement with our chronology. K/Ba and K/Rb values within this zone are relatively low and fall between the ranges for Iowa loess and Indiana loess. This implies a lesser contribution from the Green Bay Lobe than is apparent in zone p-5 and a relatively greater contribution from a western source, such as the Des Moines lobe. Such an interpretation is consistent with the glacial history. At the time of accumulation of loess in this zone at Morrison, the Green Bay Lobe had retreated northward (Mickelson and Attig, 2017), but the Des Moines Lobe had advanced well into central Iowa (Fig. 26). Thus, Des Moines Lobe outwash was likely delivered to the upper Mississippi River via tributaries in southeastern Minnesota and there was apparently a diminished supply of Green Bay lobe outwash to the Mississippi from the northeast. The relative contribution of northern lobes to the upper Mississippi River at this time cannot be determined. Northern lobe tills have relatively high smectite and low dolomite content (Grimley, 2000), but as discussed above, the range of K/Ba and K/Rb values would permit, but not require, contributions from these sources.

5.4. Rapids City, Illinois

The loess section at Rapids City occupies an interesting position with respect to the Mississippi River. As noted earlier, prior to the Mississippi River diversion to its present course at ~24.4 ka, Rapids City would not have had a major outwash source upwind (i.e., to the northwest; Figs. 3 and 25). Once diversion of the river took place however, Rapids City would have been immediately downwind of what is now the Mississippi River valley.

Carbonate data allow us to recognize four zones within Peoria Loess at Rapids City, which we correlate to McKay's (1977, 1979a) zones p-2, p-3, p-5, and p-6 (Figs. 18 and 21). The upper three zones at Rapids City correspond to the three zones at Morrison and are supported by the radiocarbon ages at both localities. An age of ~23.1 ka within what we call zone p-3 at Rapids City is identical to one that we infer to be zone p-3 at Morrison (Fig. 21). An age of ~21.2 ka at the base of what we consider to be zone p-5 at Rapids City is not significantly different from an age of ~21.5 ka at the base of what we infer to be zone p-5 at Morrison. Clay mineralogy is consistent with the carbonate mineralogy in these three zones, with intermediate, high, and low mica (illite) zones corresponding to intermediate (p-3), high (p-5), and low (p-6) dolomite zones (Fig. 18). On the basis of the mineralogical data, therefore, we infer the same general history for the upper three zones at Rapids City as we hypothesize for Morrison.

There are, however, two important differences between the two sections. One is that in the "high" dolomite zone p-5 at Rapids City, total carbonate contents (as measured by CaO + MgO + LOI and equivalent $CaCO_3$) are somewhat lower than they are within the equivalent p-5 zone at Morrison (Fig. 21). One possible explanation for this is that sedimentation rates might have been lower at Rapids City, resulting in syndepositional leaching. However, this explanation is not supported by K/Ba and K/Rb values, which are also lower in zone p-5 at Rapids City (intermediate between Iowa loess and Indiana loess ranges) than they are within zone p-5 at Morrison (Figs. 21 and 23). This implies that Rapids City was receiving a somewhat greater proportion of western lobe and/or northern lobe sediments during p-5 time than at Morrison.

Another significant difference between the two localities is the presence of a thin (~1 m) depth interval, correlated with McKay's (1977, 1979a) p-2 dolomite zone, at the base of the Rapids City section. At Morrison, there is no evidence of such a zone. The basal zone at Rapids City has high dolomite, high total carbonate, high mica, and the highest K/Ba and K/Rb values of the entire section. Two calibrated radiocarbon ages of 25.4 ± 0.2 (on spruce needles) and 25.0 ± 0.4 ka (on wood) at 8.6 m, in the middle of this zone, imply a pre-diversion (~24.4 ka) age, if taken at face value. If this interpretation is correct, the origin of this high-dolomite, high-mica, high K/Ba and K/Rb p-2 zone is problematic, because the Ancient Mississippi River would have been *northeast* of Rapids City at ~25 ka (Figs. 3 and 25). Thus, assuming dominantly westerly or northwesterly winds during the last glacial period, a high-mica, high-dolomite eastern source would have been lacking for Rapids City. One possible explanation to reconcile these observations is that northeasterly katabatic winds, coming off the advancing Lake Michigan Lobe of the Laurentide Ice sheet, could have transported sediment from the Ancient Mississippi River valley to the southwest, including the vicinity of Rapids City. Peoria Loess measurements in this area indicate a southward thickening trend (Fig. 3a), which could support this interpretation. Katabatic winds from the Laurentide Ice Sheet have been used to explain last-glacial loess distribution in Wisconsin (Schaetzl and Attig, 2013).

An alternative explanation is that the ~25 ka radiocarbon ages from this zone are simply not significantly different from the age of the diversion of the Mississippi River. Age estimates of this

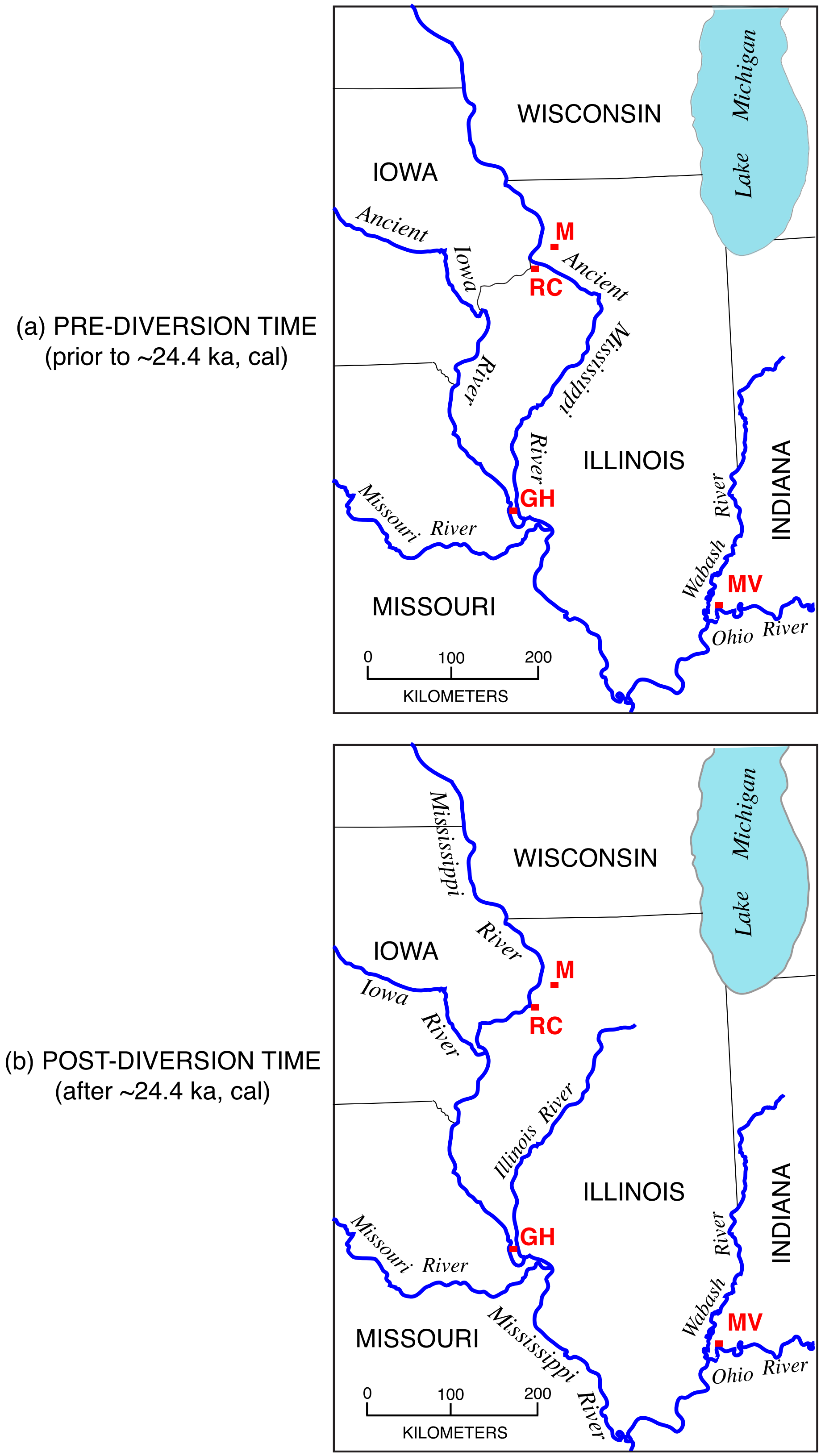

Fig. 25. (a) Simplified diagram showing location of the “Ancient Mississippi River” and the “Ancient Iowa River” prior to the diversion of the Mississippi River by the Lake Michigan Lobe of the Laurentide Ice Sheet at ~24.4 ka, slightly modified from Frye et al. (1968). (b) Same region as shown in (a) but with modern positions of rivers. Also shown, on both diagrams, are locations of loess sections studied: M, Morrison; RC, Rapids City; GH, Greenbay Hollow; MV, Mount Vernon.

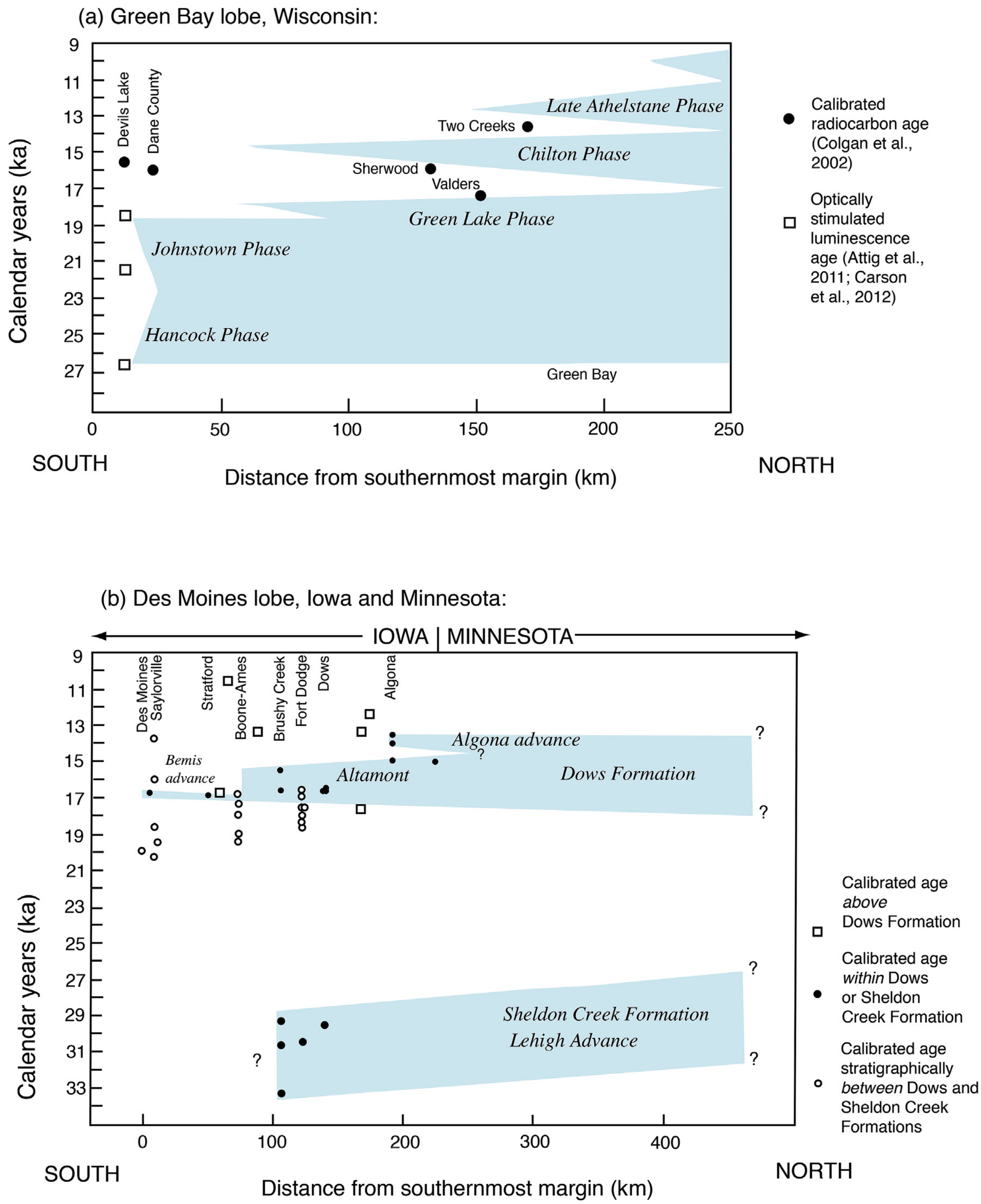

Fig. 26. (a) Time-distance diagram of the Green Bay Lobe of the Laurentide Ice Sheet from ~26 ka to ~9 ka; all ages are in calibrated radiocarbon years (filled circles) or are optically stimulated luminescence (OSL) ages (open squares). Redrawn from Colgan et al. (2002) and Syverson and Colgan (2004), with modifications based on new OSL ages from Attig et al. (2011) and Carson et al. (2012). (b) Time-distance diagram of the Des Moines Lobe of the Laurentide Ice Sheet from ~35 ka to ~9 ka; all ages are in calibrated radiocarbon years. Data for all Dows Formation ages are from the compilation by Bettis et al. (1996); Sheldon Creek Formation ages are from this study (Table 1).

diversion are ~24.4 ± 0.1 ka (Curry, 1998) and 24.4 ± 2 ka (Nash et al., 2018). In the latest analysis of the existing data, however, the maximum estimated age of this event could be as old as 25.1 ka (see Curry et al., 2018, their Table 2). Thus, it is possible that the thin, high-dolomite, high-mica, p-2 zone at Rapids City might mark the earliest loess accumulation derived from the post-diversion Mississippi River valley. If so, then it is likely that this influx of silt was dominated by a Green Bay Lobe source, as Rapids City is north of any drainages that would have carried outwash from the Lake Michigan Lobe to the Mississippi River (Figs. 3 and 24). The Green Bay Lobe was at its maximum position south at ~25–24 ka (Attig et al., 2011; Carson et al., 2012; Mickelson and Attig, 2017; see Fig. 26a), which is consistent with this interpretation. At this point, we have no basis for favoring one or the other of these two hypotheses, but both of these intriguing explanations invite further studies in the Rapids City area.

5.5. Greenbay Hollow, Illinois

Owing to its more southerly location, the loess at Greenbay Hollow could have had sources from a number of ice lobes (Fig. 24). Whereas Morrison and Rapids City are situated north of where the Mississippi River valley could have received sediment from streams draining the Lake Michigan Lobe (such as the Rock River), Greenbay Hollow could have received pre-diversion sediment from the western lobe sources, such as the Des Moines Lobe, via the "Ancient Iowa River" (Frye et al., 1968) and post-diversion sediment from the Des Moines Lobe, the northern lobes, the Green Bay Lobe, or the Lake Michigan Lobe, all via the post-diversion Mississippi River (Figs. 24 and 25).

On the basis of their measurements, Grimley et al. (1998) interpreted different sources for lower, middle, and upper Peoria Loess at their Illinois River valley localities, which presumably include Greenbay Hollow. In their interpretations, lower Peoria Loess is pre-diversion, derived mainly from Superior and Lake Michigan Lobe sources; middle Peoria Loess (post-diversion) is considered to be derived mainly from the Lake Michigan Lobe; and upper Peoria Loess is inferred to be derived from the Lake Michigan Lobe, with possibly some Green Bay lobe influence. K/Ba and K/Rb data from the present study certainly permit an interpretation of a mix of Lake Michigan and Superior Lobe sources for lower Peoria Loess at Greenbay Hollow (Fig. 22), if some Superior Lobe sediment that was provided was within the lower range of K/Ba and K/Rb values for this till shown in Fig. 9. An alternative interpretation is that the intermediate K/Ba values in the lower Peoria Loess at Greenbay Hollow derive from a mix of high K/Ba and K/Rb Lake Michigan Lobe sediment and inputs of low K/Ba and K/Rb sediments from the western lobes, delivered via the "Ancient Iowa River." In either case, however, inputs from a Lake Michigan Lobe source at this time would have required northerly winds, rather than northwesterly or westerly winds, given the configuration of the Ancient Mississippi River at that time, occupying what is now the Illinois River (Fig. 25). Grimley et al. (1998) interpret middle Peoria Loess to reflect the diversion of the Mississippi River, with major inputs from the Lake Michigan lobe. Carbonate data presented here (proxied by CaO + MgO + LOI) and K/Ba and K/Rb values in middle Peoria Loess at Greenbay Hollow are in good agreement with this interpretation, although K/Ba and K/Rb values from ~4.0 to 5.0 m depth imply some western source influence as well. Because this depth interval falls into the post-diversion time period, the Mississippi River was situated where it is today, west of Greenbay Hollow, and would have been receiving sediment from a number of rivers in eastern Iowa that were draining the Des Moines Lobe (Fig. 24). Grimley et al. (1998) interpret upper Peoria Loess to reflect mainly a Lake Michigan Lobe source, with possibly some

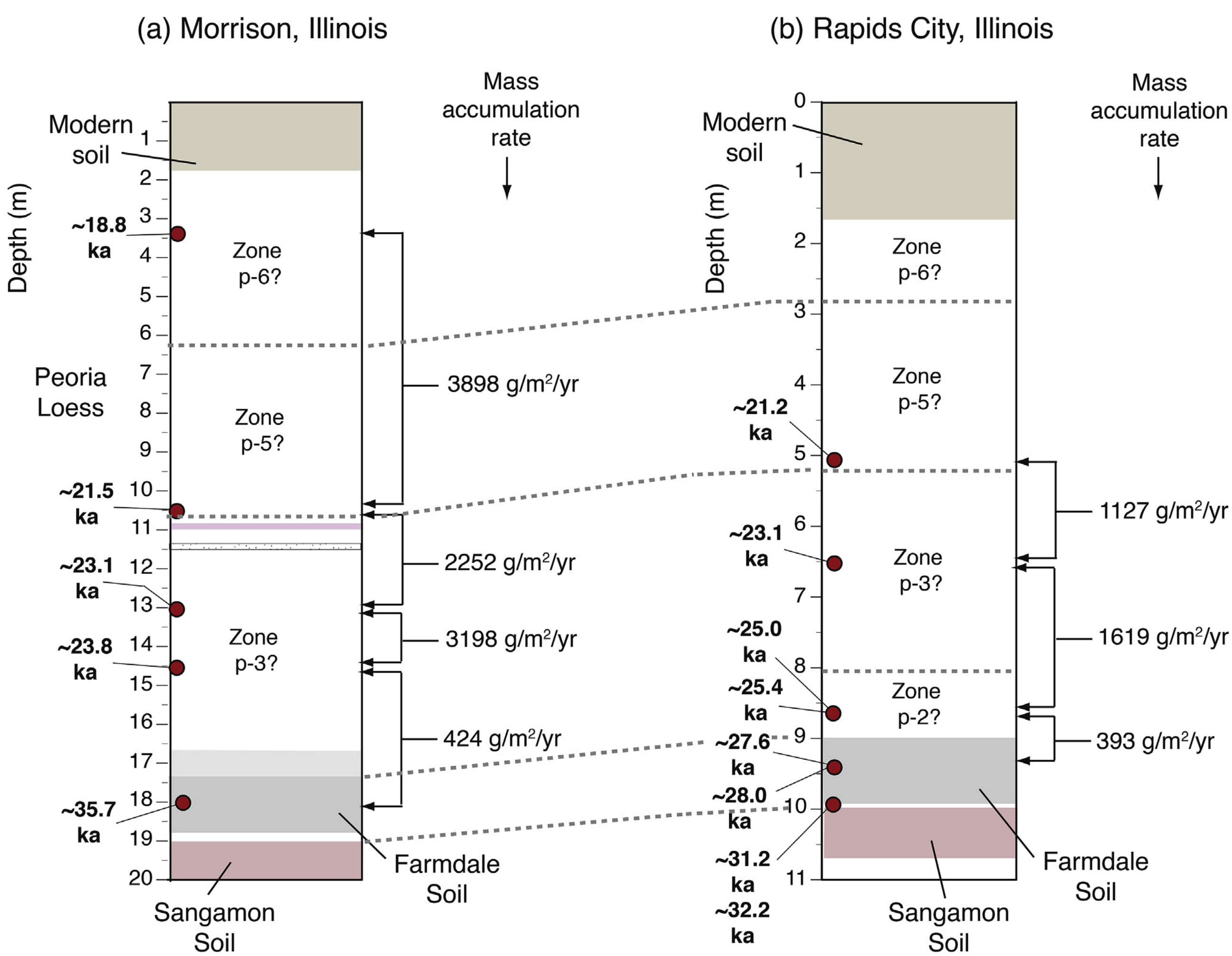

Fig. 27. Stratigraphy of the (a) Morrison and (b) Rapids City loess sections, calibrated radiocarbon ages, possible dolomite zones of McKay (1977, 1979a), and mass accumulation rates within dated depth intervals. Note that because of where the oldest datable materials were found, the lowest mass accumulation rates of both sections include parts of the Farmdale Soil/Roxana Silt; thus, these are strictly minimum rates for the oldest depth intervals of Peoria Loess.

Green Bay Lobe influence. Again, both carbonate data and K/Ba and K/Rb data from the present study are in agreement with this interpretation, but also require some western source input. During upper Peoria Loess time, the Des Moines Lobe was reaching its southernmost extent in Iowa (Fig. 26) and many of the rivers of eastern Iowa, tributaries to the Mississippi River, would have been draining this source (Fig. 24).

5.6. Mass accumulation rates of loess in the upper Mississippi River valley

The radiocarbon chronology presented here allows calculation of mass accumulation rates (MARs) for loess during the last glacial period in the upper Mississippi River valley. Mass accumulation rates of loess are key measurements for comparison with atmospheric general circulation model reconstructions of dust production during the past (e.g., Mahowald et al., 2006). Here, we calculate these rates only for the Morrison and Rapids City sections, as the chronology for Greenbay Hollow is based on correlation rather than any direct dating. We use calibrated radiocarbon ages (Table 1), section thicknesses as measured in our cores, and assume a loess bulk density of 1.45 g/cm^3, similar to what has been used in previous studies (Bettis et al., 2003; Muhs et al., 2003, 2013; Roberts et al., 2003). Bulk density measurements made on unaltered Peoria Loess from other localities ($n = 15$) in northwestern Illinois range from 1.38 to 1.58 g/cm^3, and average about 1.47 g/cm^3 (Wascher et al., 1971), in good agreement with our assumed value.

Results show that at Morrison, in those zones above the Farmdale Soil where we have age control, MARs range from 2252 g/cm^3 to 3898 g/cm^3 (Fig. 27). MARs are approximately half this in the shorter section at Rapids City, 1127 g/cm^3 to 1619 g/cm^3. Set within the context of global loess accumulation rates of the last glacial period (see supplementary data Table S1 of Mahowald et al., 2006), the MARs of Morrsion and Rapids City are high compared to most localities in China (~60–1720 g/cm^3; one locality >5000 g/cm^3), Russia (~20–1010 g/cm^3), Europe (~200–1300 g/cm^3; one locality >2000 g/cm^3), South America (~45–145 g/cm^3), and Alaska (~6–210 g/cm^3). Nevertheless, the rates are not as high as some reported for dominantly non-glaciogenic loess of the central Great Plains (~5000–6000 g/cm^3; Roberts et al., 2003), nor are they as high as some rates reported for dominantly glacial (but partially non-glacial) loess of western Iowa, adjacent to the Missouri River (~6000 g/cm^3; Bettis et al., 2003; Muhs et al., 2013).

There has long been a debate about the relative importance of glacial sources of loess versus non-glacial ("desert") sources of loess (see review in Muhs, 2013). The traditional model of loess being tied to glaciers is supported by modern field studies that show glaciated valleys having significantly higher sediment yields than adjacent unglaciated valleys (Hallet et al., 1996). On the other hand, experimental work shows that non-glacial processes are surprisingly efficient producers of silt (Wright, 2001). Furthermore, particle size inventories in the sedimentary rock record reveal that fully half the particles are of silt size (Blatt, 1987). Thus, simple inheritance from silt-dominated rocks can be a major factor in loess sources, and inheritance from siltstones in fact explains the origin of much of the loess in the central Great Plains (Aleinikoff et al., 1999, 2008; Muhs et al., 2008a). Based on the mineralogy and geochemistry presented here, there is little question that loess in the upper Mississippi River Basin is dominantly of glaciogenic origin, derived from lobes of what was the largest ice sheet in the Northern Hemisphere during the last glacial period. The Morrison and Rapids City sections host some of the thickest Peoria Loess in the Mississippi River valley, yet the MARs for these sections are lower than those for non-glacial loess at several localities in the Great Plains.

6. Conclusions

The studies of loess and their K/Rb and K/Ba compositions from diverse parts of North America, and specifically for the upper Mississippi River valley, lead us to the following conclusions:

(1) K-bearing minerals (K-feldspar and micas) contain Rb and Ba as trace elements that follow K, and therefore K/Rb and K/Ba values will vary with mineralogy and source rock history. Loess from widely separated parts of North America should have K/Rb and K/Ba values that differ because of the contrasting geology that provided the source sediments. Analyses of such loess bodies from various parts of North America (Alaska, Wyoming, Colorado, Nebraska, Iowa, Indiana, and Ohio) show that this is indeed the case, demonstrating the potential for use of these ratios as provenance indicators.

(2) Loess bodies that are known to have the same source sediments, based on independent lines of evidence, such as isotopic methods, should yield K/Rb and K/Ba values that are similar. This hypothesis has been tested using loesses from eastern Colorado and Nebraska. The results indicate that there is no significant difference in K/Rb and K/Ba values, which supports the use of these as provenance indicators.

(3) Study of three thick loess sections along the upper Mississippi River valley confirms that the traditional parameters used to characterize changing loess compositions, carbonate mineralogy and clay mineralogy, vary as a function of depth, indicating changing source sediments.

(4) Analyses of the K/Rb and K/Ba values in loess from these same sections are consistent with the results rendered by traditional methods. K/Ba and K/Rb values show vertical variations that closely parallel those of carbonate mineral (dolomite) and clay mineral (mica) abundances. These observations show that at times, particular ice lobes were dominant sources whereas at other times, other lobes were dominant loess sources. However, the data presented here also show that there is considerable complexity in these loess sections, with evidence that both western and eastern lobes (and possibly northern lobes) contributed source sediments at the same times.

(5) Mass accumulation rates in upper Mississippi River loess sections range from ~1100 g/m^2/yr to ~3900 g/m^2/yr. These rates are higher than most rates reported for loess accumulation in China, Russia, Europe, South America, and Alaska. However, the rates for the upper Mississippi River valley are lower than those for a number of localities in the Great Plains region of Nebraska, where loess is dominantly of a non-glacial origin and the Missouri River Basin area of western Iowa, where loess is partly derived from glacial sources and partly from non-glacial sources.

The close association between the distinctive mineralogy and geochemistry of tills and outwash, and different glacial lobes, as reflected in changes in loess composition over time, shows that the patterns of loess provenance and accumulation during a single glacial period can be very complex. Simple geochemical indicators, K/Rb and K/Ba, can track this compositional complexity closely in the upper Mississippi River Basin and are highly complementary to other tools that have been used for loess provenance such as carbonate mineralogy, clay mineralogy, and magnetic susceptibility. We therefore encourage a similar approach to studying the compositional history of loess accumulations in other parts of the world, including China, Central Asia, Russia, Europe, Argentina and New Zealand.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.quascirev.2018.03.024.

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